Mobile Communications
Chapter 3 : Medium Access Control

- Motivation
- SDMA, FDMA, TDMA
- Aloha
- Reservation schemes
- Collision avoidance, MACA
- Polling
- CDMA
- SAMA
- Comparison

Motivation

Can we apply media access methods from fixed networks?

Example CSMA/CD

- **C**arrier **S**ense **M**ultiple **A**ccess with **C**ollision **D**etection
- send as soon as the medium is free, listen into the medium if a collision occurs (original method in IEEE 802.3)

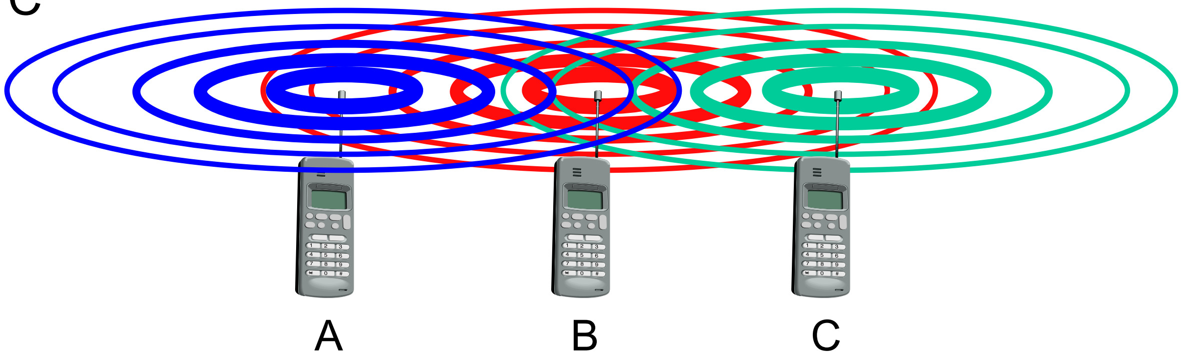
Problems in wireless networks

- signal strength decreases proportional to the square of the distance
- the sender would apply CS and CD, but the collisions happen at the receiver
- it might be the case that a sender cannot “hear” the collision, i.e., CD does not work
- furthermore, CS might not work if, e.g., a terminal is “hidden”

Motivation - hidden and exposed terminals

Hidden terminals

- A sends to B, C cannot receive A
- C wants to send to B, C senses a “free” medium (CS fails)
- collision at B, A cannot receive the collision (CD fails)
- A is “hidden” for C



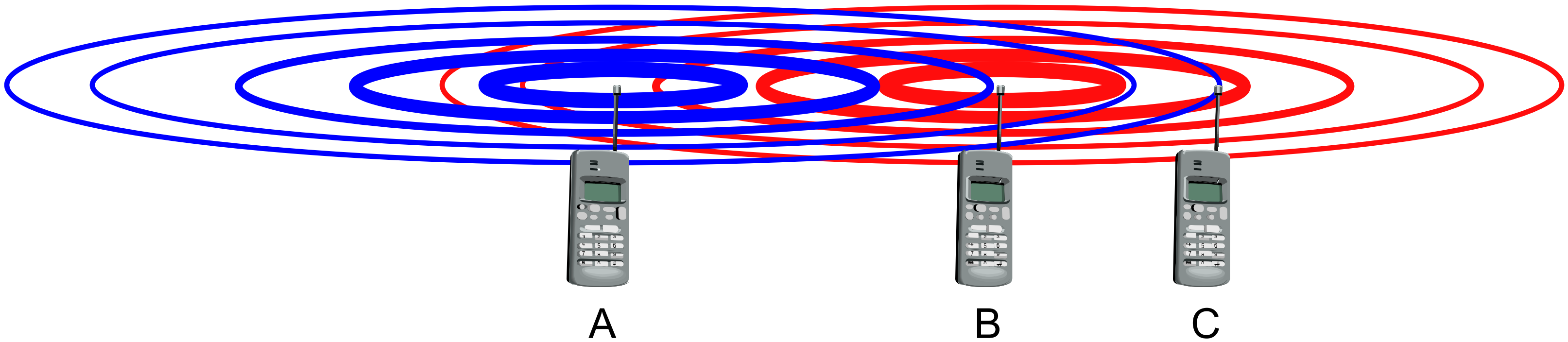
Exposed terminals

- B sends to A, C wants to send to another terminal (not A or B)
- C has to wait, CS signals a medium in use
- but A is outside the radio range of C, therefore waiting is not necessary
- C is “exposed” to B

Motivation - near and far terminals

Terminals A and B send, C receives

- signal strength decreases proportional to the square of the distance
- the signal of terminal B therefore drowns out A’s signal
- C cannot receive A



If C for example was an arbiter for sending rights, terminal B would drown out terminal A already on the physical layer

Also severe problem for CDMA-networks - precise power control needed!

Access methods SDMA/FDMA/TDMA

SDMA (Space Division Multiple Access)

- segment space into sectors, use directed antennas
- cell structure

FDMA (Frequency Division Multiple Access)

- assign a certain frequency to a transmission channel between a sender and a receiver
- permanent (e.g., radio broadcast), slow hopping (e.g., GSM), fast hopping (FHSS, Frequency Hopping Spread Spectrum)

TDMA (Time Division Multiple Access)

- assign the fixed sending frequency to a transmission channel between a sender and a receiver for a certain amount of time

The multiplexing schemes presented in chapter 2 are now used to control medium access!

Some medium access control mechanisms for wireless

- SDMA
- TDMA
  - Fixed
    - Used in GSM
  - Aloha
    - Pure
    - Slotted
  - CSMA
    - Non-persistent
    - p-persistent
    - CSMA/CA
      - Used in 802.11 (mandatory)
  - Reservations DAMA
  - Multiple Access with Collision Avoidance
    - Copes with hidden and exposed terminal
    - RTS/CTS
    - Used in 802.11 (optional)
    - MACAW
    - MACA-BI
    - FAMA
      - CARMA
  - Polling
    - Used in 802.11 (optional)
- FDMA
  - Fixed
    - Used in GSM
  - FHSS
    - Used in Bluetooth
- CDMA
  - FHSS
  - DSSS
    - Used in UMTS

FHSS: Frequency-Hopping Spread Spectrum
DSSS: Direct Sequence Spread Spectrum
CSMA: Carrier Sense Multiple Access
CA: Collision Avoidance
DAMA: Demand-Assigned Multiple Access
MACA-BI: MACA by invitation
FAMA: Floor Acquisition Multiple Access
CARMA: Collision Avoidance and Resolution Multiple Access

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FHSS: Frequency-Hopping Spread Spectrum
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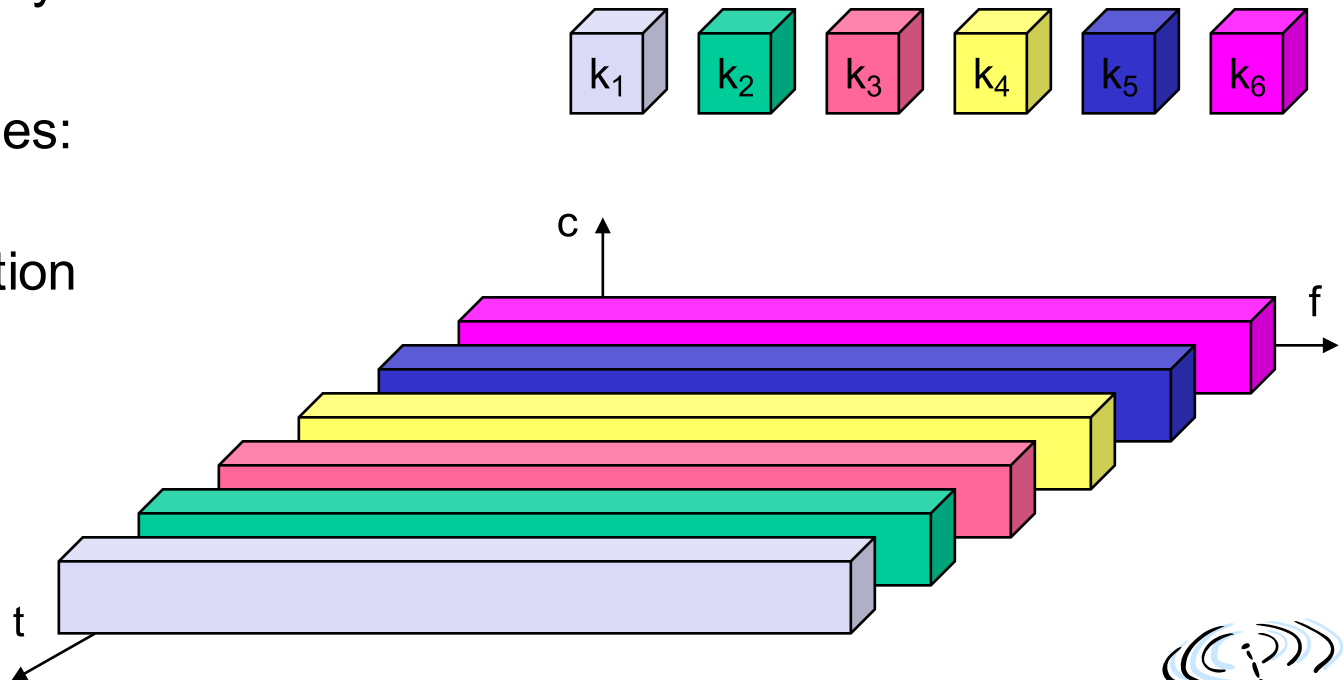
Time multiplex

- A channel gets the whole spectrum for a certain amount of time.

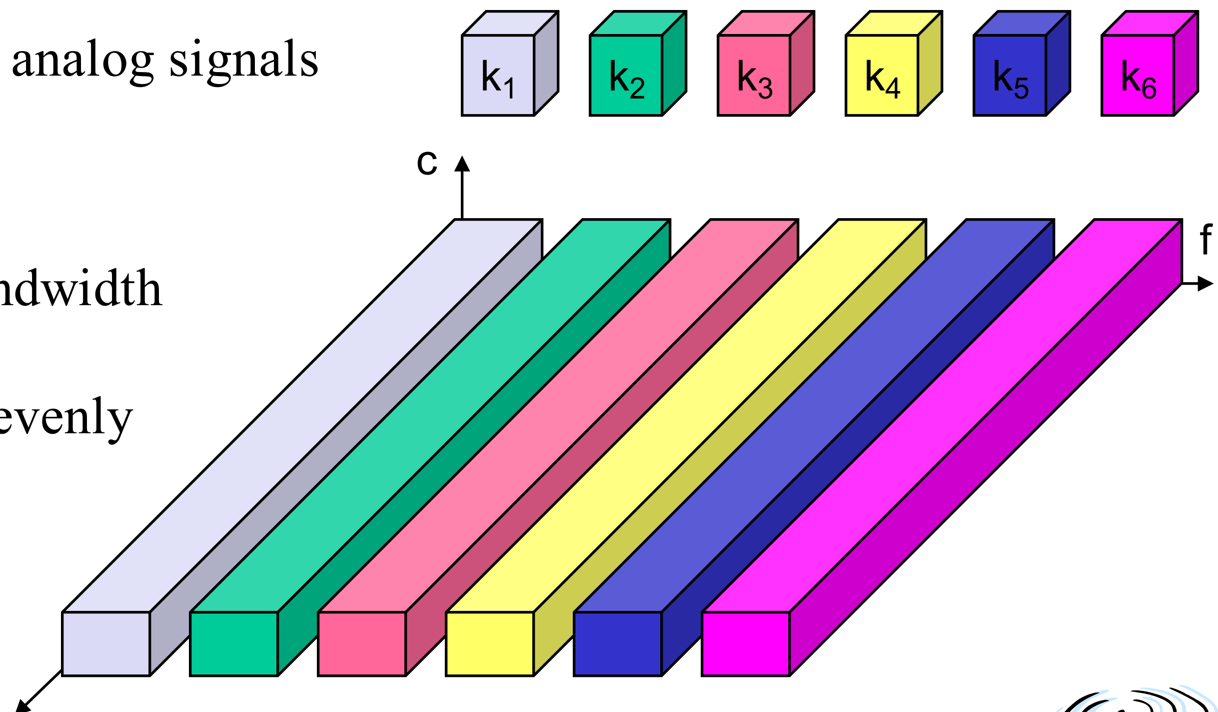
- Advantages:
  - only one carrier in the medium at any time

- Disadvantages:
  - precise synchronization required



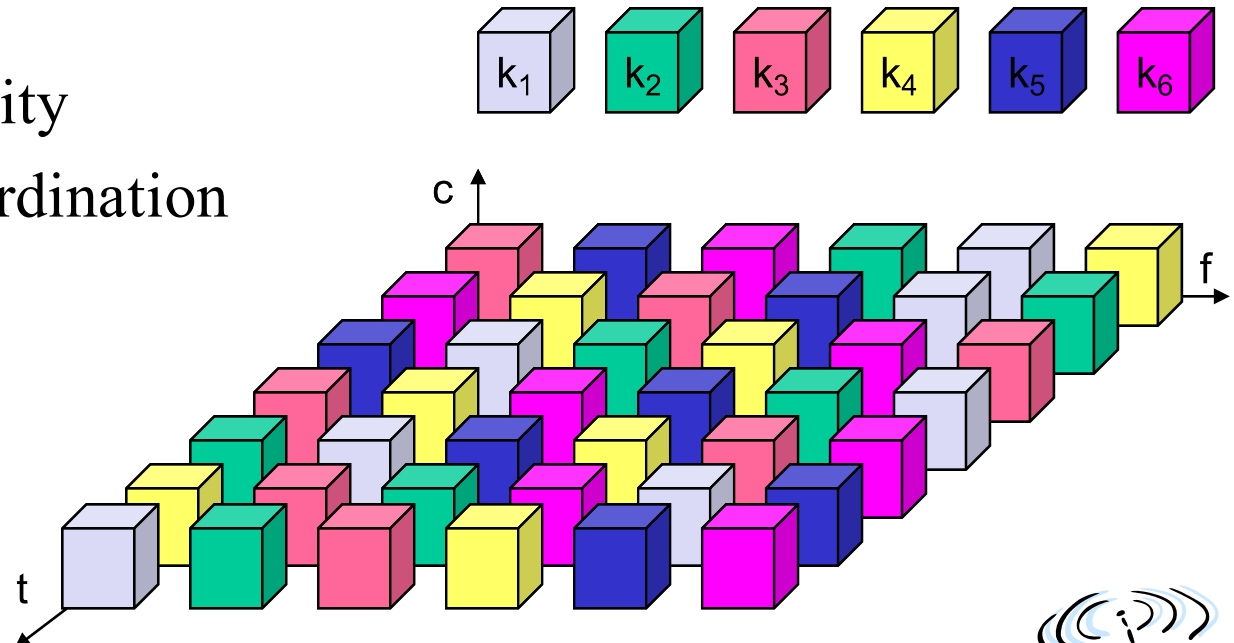
Frequency multiplex

- Separation of the whole spectrum into smaller frequency bands.
- A channel gets a certain band of the spectrum for the whole time.
- Advantages:
  - looser coordination
  - works also for analog signals
- Disadvantages:
  - wastage of bandwidth if the traffic is distributed unevenly
  - inflexible
  - guard spaces



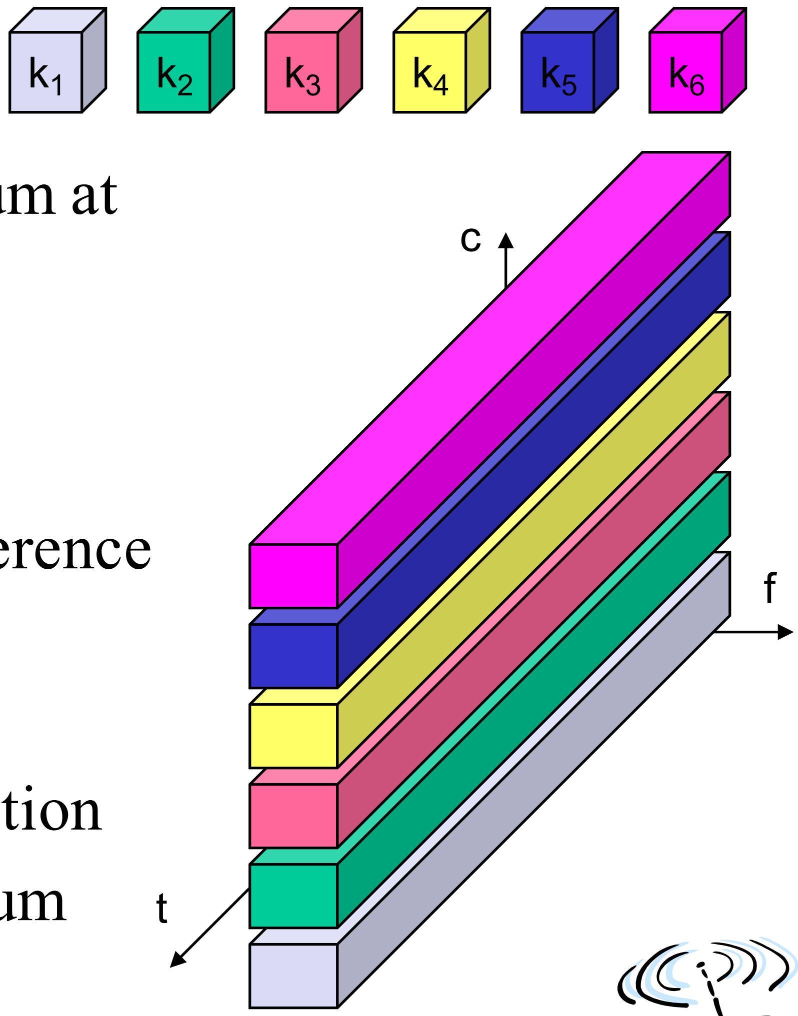
Time and frequency multiplex

- Combination of both methods.
- A channel gets a certain frequency band for a certain amount of time.
- Example: GSM
- Advantages:
  - more flexibility
- But: precise coordination required



Code multiplex

- Each channel has a unique code
- All channels use the same spectrum at the same time
- Advantages:
  - bandwidth efficient
  - good protection against interference and eavesdropping
- Disadvantage:
  - more complex signal regeneration
- Implemented using spread spectrum technology



Multiple Access

- Term has its Origin in Satellite Communications
- System of Earth Stations and a Satellite
- Used to Mean Sharing a Communications Channel (of M Hz) among a Group of Users
- Signal Space of Time Bandwidth TW
  - Where T = k/R
  - Signal Space D = 2TW

Partition of Signal Space

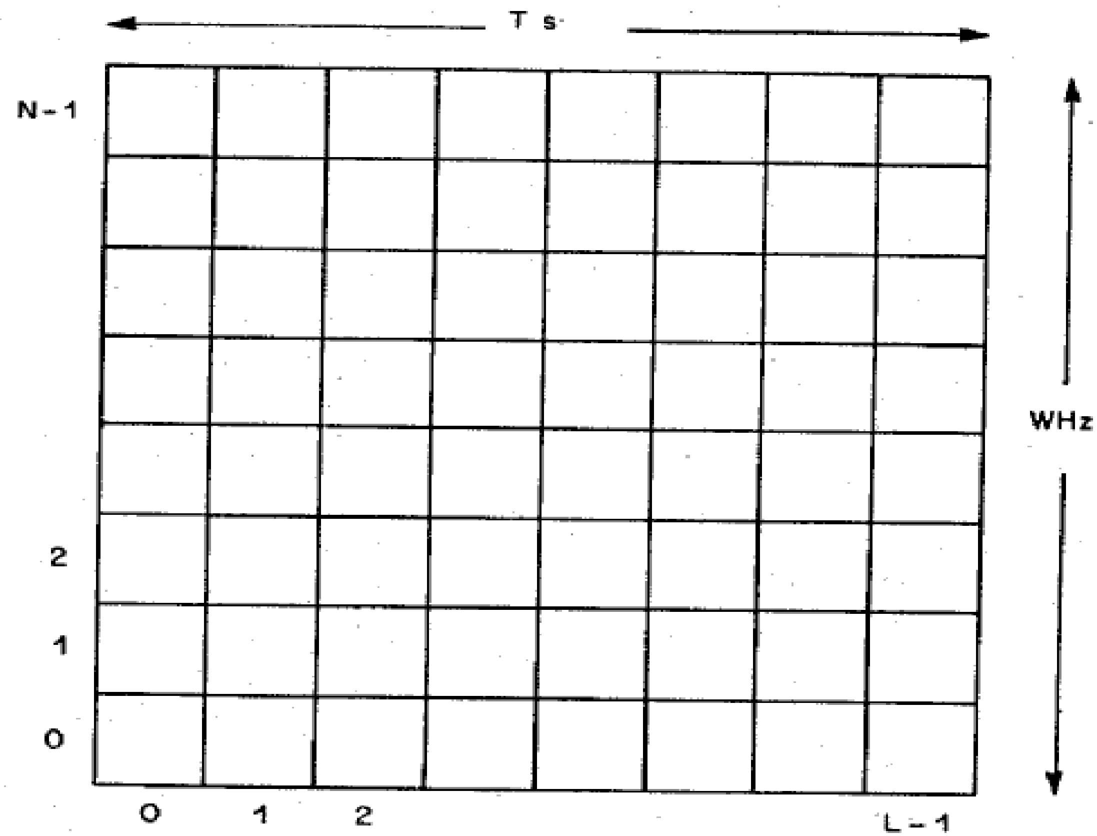
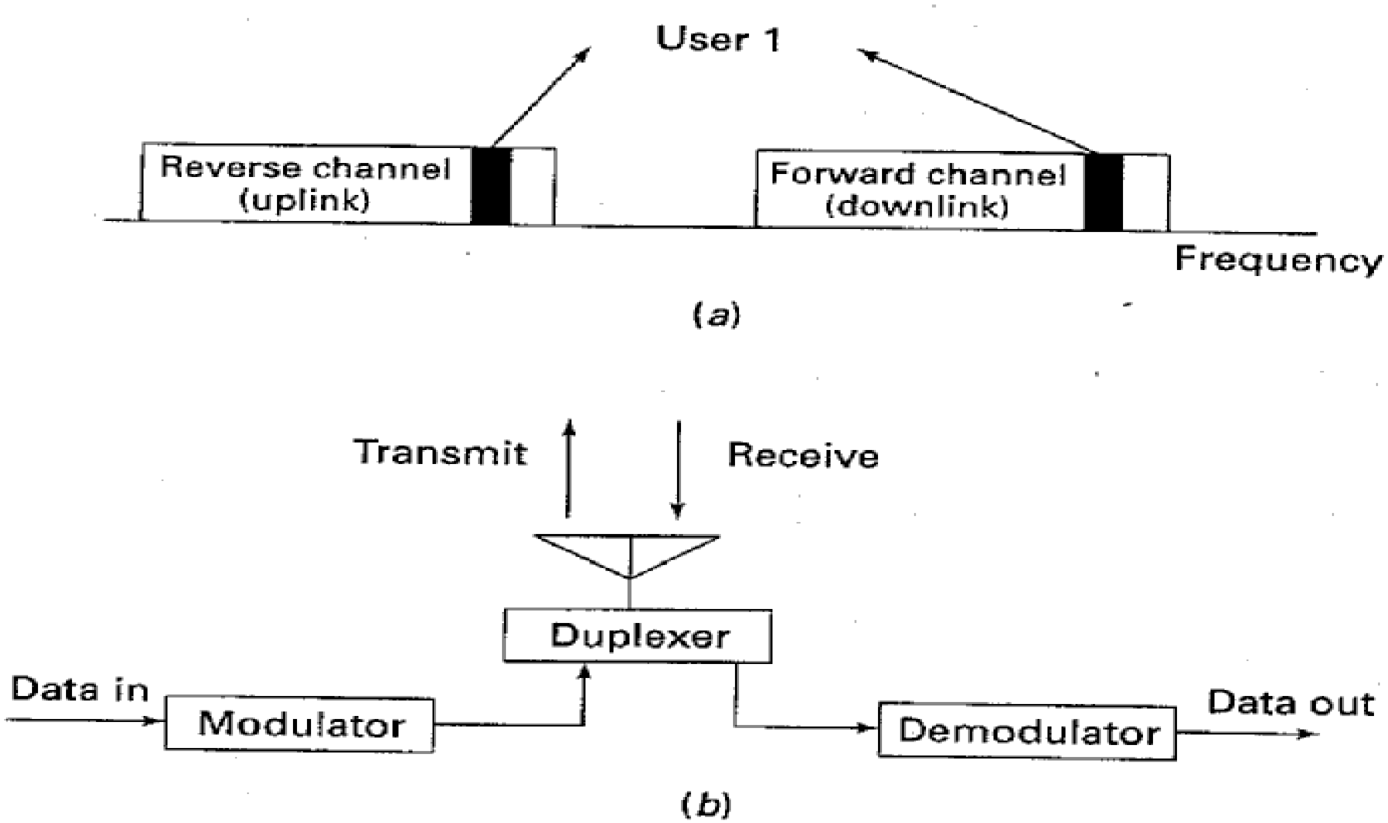


Fig. 1. Partition of signal space with time–bandwidth product TW into NL cells. Number of information bits per frame period (T) is $k = RT$, where R b/s is user bit rate. N frequency channels exist with spacing τ^{-1} Hz and L time slots, each of duration τ s, such that each cell has unit time–bandwidth product.

Duplex Transmission

- Frequency Division Duplexing



Frequency/Time Division Duplexing

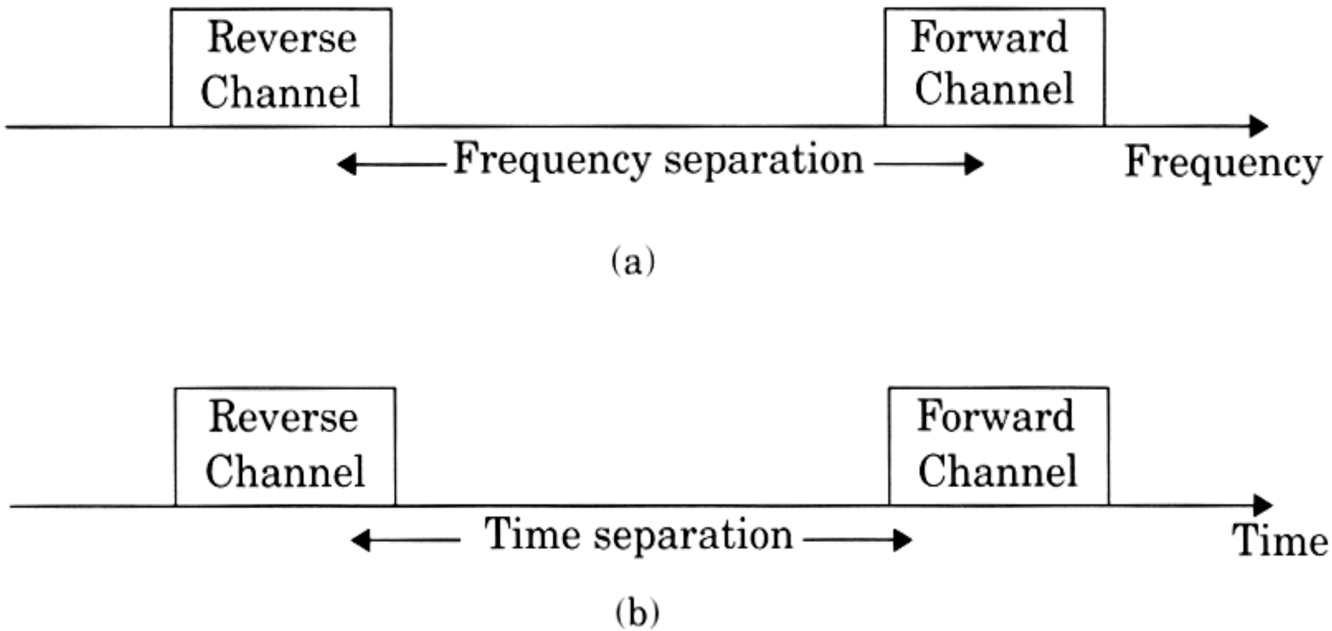


Figure 9.1 (a) FDD provides two simplex channels at the same time; (b) TDD provides two simplex time slots on the same frequency.

Trade-offs between FDD and TDD

- Frequency Division Duplexing
  - Geared toward Individual Channels for each User
  - Frequency Separation must use Inexpensive Technology
- Time Division Duplexing
  - Eliminates Need for Forward and Reverse Channels
  - Time Latency

Multiple Access Techniques

- Frequency Division Multiple Access (FDMA)
- Time Division Multiple Access (TDMA)
- Code Division Multiple Access   (CDMA)
- Grouped as Narrowband or Wideband Systems

Narrowband Systems

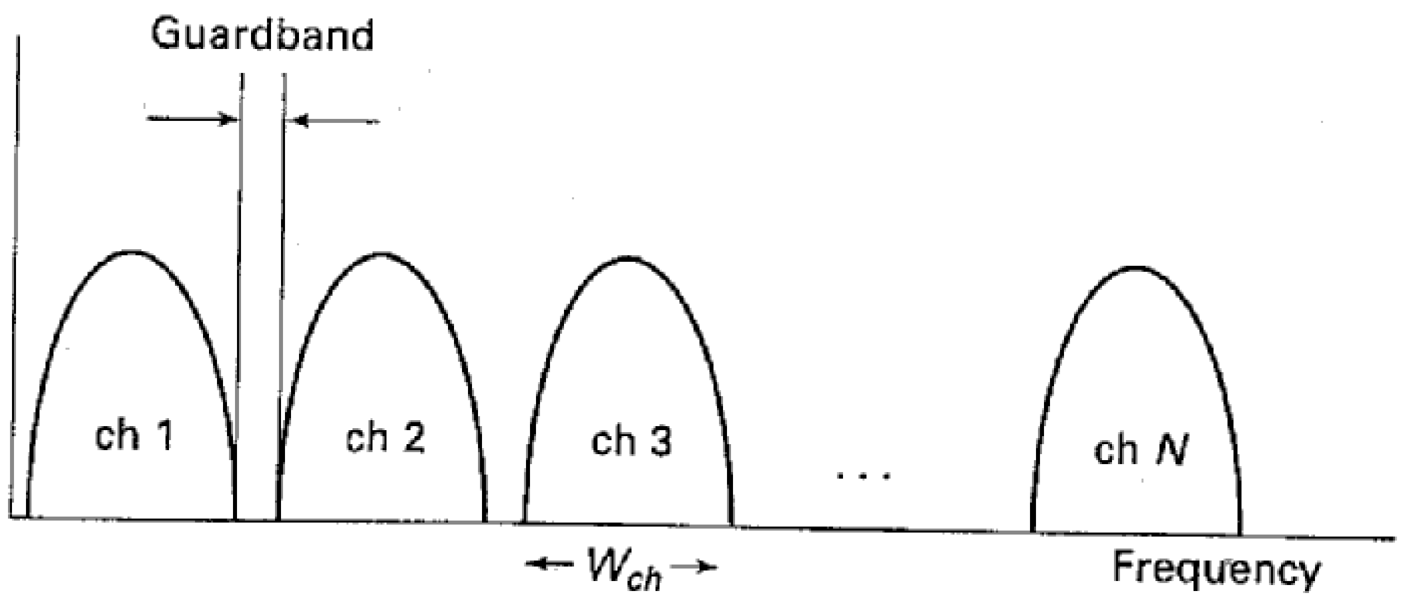
- "Narrow" relates single channel BW to coherent BW
- Normally operated using Frequency Division Duplexing
- Narrowband FDMA
  - Channel not Shared with other users
  - Called FDMA/FDD Access Systems
- Narrowband TDMA
  - Users Separated by Time
  - Called TDMA/FDD or TDMA/TDD Access Systems

Wideband Systems

- Transmission BW is much larger than Coherence BW
- Multipath Fading is not a Problem
- Users Transmit in a Large Part of the Spectrum
- Many Transmitters use the Same Channel using TDMA
- TDMA Allocates Time Slots

Frequency Division Multiple Access

- Users Receive Unique Channel
- Channels Assigned as Users Request Service



FDMA vs. TDMA

- If an FDMA channel not in use, it is idle, and can not be used by other users.
- After the assignment the reverse and forward channel may transmit simultaneously and continuously
- FDMA implemented as Single channel per carrier (SCPC), and is narrow band 30 KHz
- The symbol time is large as compared to average delay spread. ISI is low, and no equalization required for NB FDMA
- FDMA mobile system is less complex as compared to TDMA. Due to advancement in DSP this is changing
- FDMA is continuous tx scheme, so fewer overhead bits are required as compared to TDMA
- FDMA systems have higher cell site costs as compared to TDMA, because of SCPC in FDMA, and use of expensive pass band filters to eleminate the spurious radiations at base stations.
- The FDMA mobile unit uses duplexers, since both TX and RCVR operate at the same time, resulting in an incresae in the cost of mobie units and base stations
- FDMA requires tight RF filtering to minimize adjacent channel interference

Multiple Access Techniques used in wireless systems

Table 9.1 Multiple Access Techniques Used in Different Wireless Communication Systems

Cellular System	Multiple Access Technique
Advanced Mobile Phone System (AMPS)	FDMA/FDD
Global System for Mobile (GSM)	TDMA/FDD
US Digital Cellular (USDC)	TDMA/FDD
Pacific Digital Cellular (PDC)	TDMA/FDD
CT2 (Cordless Telephone)	FDMA/TDD
Digital European Cordless Telephone (DECT)	FDMA/TDD
US Narrowband Spread Spectrum (IS-95)	CDMA/FDD
W-CDMA (3GPP)	CDMA/FDD CDMA/TDD
cdma2000 (3GPP2)	CDMA/FDD CDMA/TDD

Nonlinear Effects in FDMA

- Antenna at Base Station Shared by Channels
- Nonlinearities of Power Amps and Combiners
- Results in Signal Spreading
  - Generates Intermodulation
  - Causes Adjacent Channel Interference
  - And Adjacent Service Interference

Example

- Find the IM products, if base station antenna transmits 2 carrier frequencies, at 1930, and 1932 MHz, that are amplified by a saturated clipping amplifier. If mobile radi band is allocated from 1920 to 1940 Mhz, find the in-band and out of band IM products.
- Solution
- IM products are mf1+nf2 for all integer values of m and n.
- Possible IM products are:
- (2n+1)f1-2nf2, (2n+2)f1-(2n+1)f2, (2n+1)f2-2nf, (2n+2)f2-(2n+1)f1 for n=0,1,2-----

N=0	N=1	N=2	N=3
1930	1926	1922	1918
1928	1924	1920	1916
1932	1936	1940	1944
1934	1938	1942	1946

Advanced Mobile Phone System (AMPS)

- First U.S. Analog Cellular System
- Based on FDMA/FDD
- NBFM Modulates the Carrier
- Total Number of Channels is Given by:

$$N = \frac{B_t - 2B_{guard}}{B_c}$$

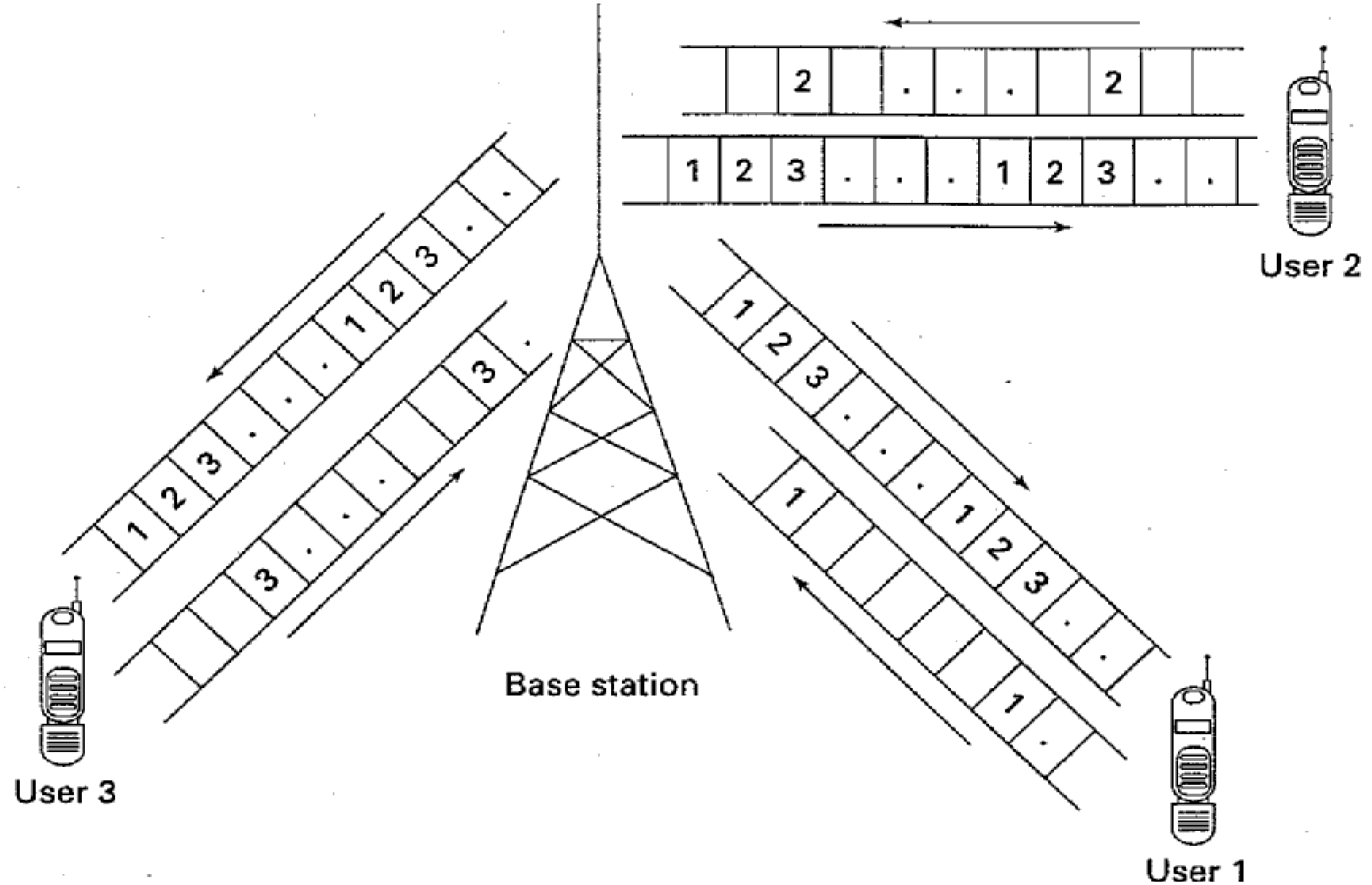
Example:
Given allocated BW =12.5 Mhz for each simplex band.
Guard band = 10 Khz, and Channel BW =30 Khz. Find the number of channels

N =(12.5*10^3-20)/30 = 416

In US each cellular carrier is allocated 416 channels

Time Division Multiple Access

- Enables Users to Use the Whole Bandwidth on a time Basis



TDMA Time Frame

- Data Transmitted in a Buffer-and-Burst Method

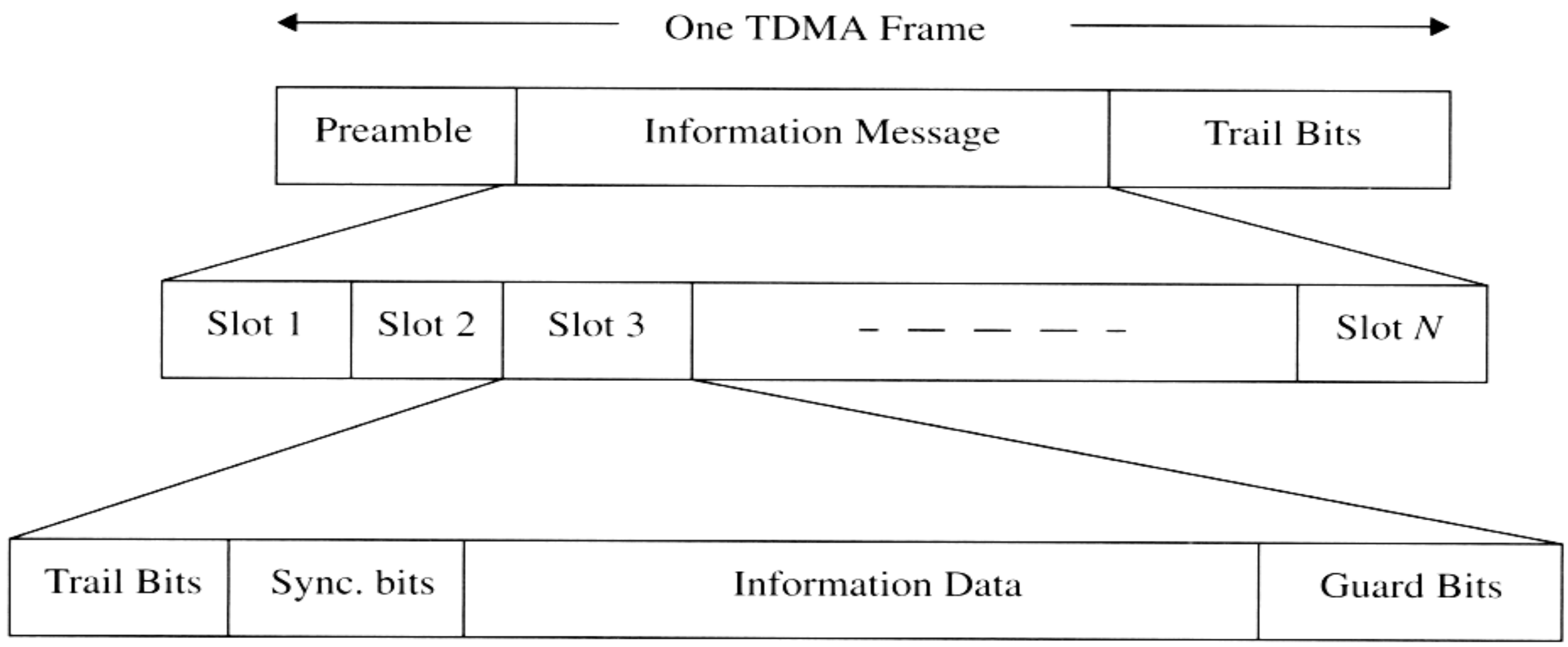


Figure 9.4 TDMA frame structure. The frame is cyclically repeated over time.

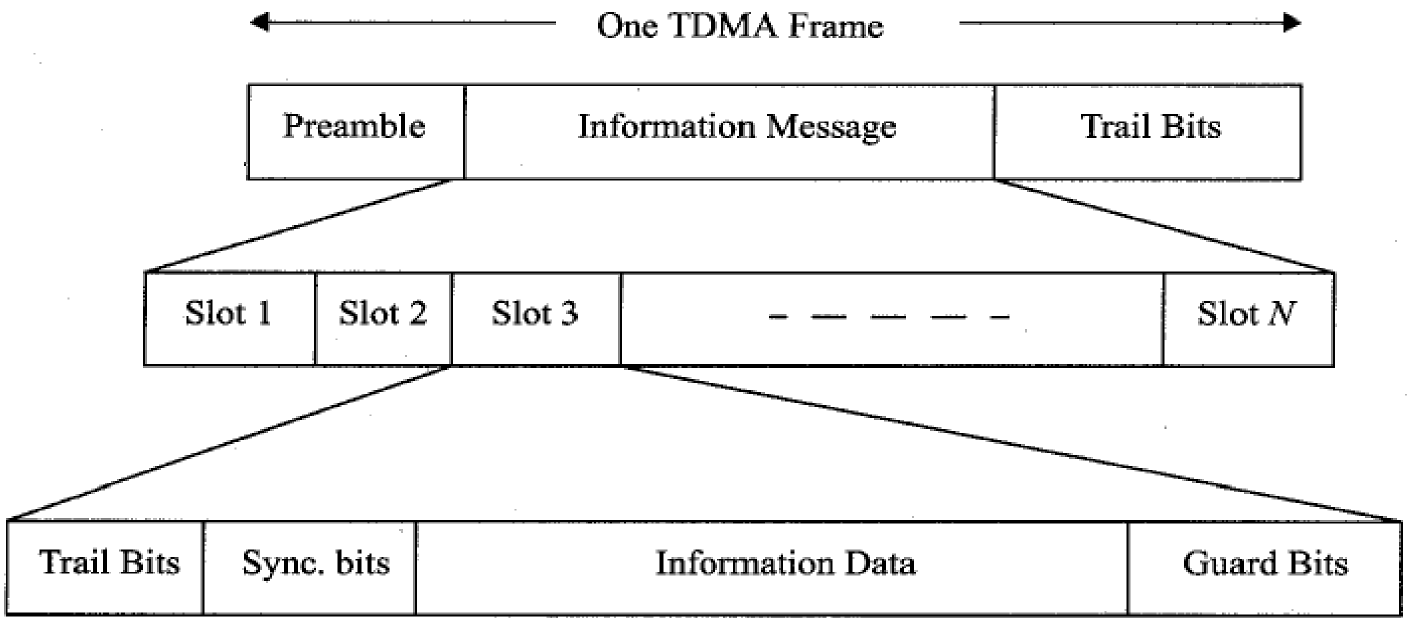
Time Division Multiple Access Features

- In TDMA a single carrier frequency with a wide bandwidth is shared among multiple users. Ecah user is assigned non-overlapping time slot.
- Number of time slots per frame depends on (1) available bandwidth, (2) modulation techniques etc
- Transmission for TDMA users is not continuous, but occurs in bursts, resulting in low battery consumption. The subscriber transmitter may be turned off during non-transmission periods
- Hand off process is simpler for a subscriber, sinc eit can listen to other base stations during non-transmit times.
  - AN ENHANCED LINK CONTROL SUCH AS THAT PROVIDED BY MAHO CAN BE implemented by a subscribet by listening in an idle time slot in the TDMA frame
  - TDMA uses different time slots for TX and reception, thus duplexers are not required.
    - Even in TDMA/FDD a switch rather than a duplexer is required in the mobile unit to switch between the TX and RCRVR

Time Division Multiple Access Features

- Adaptive equalization is usually required since Tx speed for a TDMA system is higher as compared to FDMA
- In TDMA the guard band should be minimized. IF the TX signal at the edges of a time slot are suppressed sharply in order to reduce the guard band, the TX spectrum will expand, and cause interference to the adjacent channels
- A high synchronization overhead is required, because of burst transmission.
- TDMA transmissions are slotted, this requires the receievr to be synchronized for each data burst. In addition guard slots are necessary, to separate users. TDMA systems have larger overhead as compared to FDMA
- TDMA is more flexible, as a number of time slots may be combined to give a higher capacity to a users. Further more number of slots combined can be varied for serving different user requirements. Bandwidth on demand

Efficiency of TDMA



$$b_{OH} = N_r b_r + N_t b_p + N_t b_g + N_r b_g \qquad b_T = T_f R \qquad \eta_f = \left(1 - \frac{b_{OH}}{b_T}\right) \times 100\%$$

- b_{OH} = Overhead bits
- N_r = Number of ref bursts per frame
- br = number of overhead bits per ref burst
- Nt = Traffic bursts per farme
- bp = Number of preamble bits traffic burst

Number of Channels in TDMA System

- Number of Channels is Total Number of Slots Multiplied by the Channels Available

$$N = \frac{m\,(B_{tot} - 2B_{guard})}{B_c}$$

Example

Consider GSM system: TDMA/FDD

Forward link BW = 25 MHz, which is segmented into 200 KHZ channels. IF 8 speech channels are supported on a single radio channel, Find the number of simultaneous users. Assume no guard band

Solution

Number of channels = 8* 25 *10^6/200*10^3 =1000

Example 1

- Each frame in GSM supports 8 time slots
- Each time slot transmits 156.25 bits, and data is transmitted at 270.833 Kbits in a channel, determine
  - (1) Time duration of a bit
  - (2) time duration of a slot,
  - (3) time duration of a frame,
  - (4) how long a user must wait between two transmissions, assuming the user is using one time slot
- Example 2
- TDMA efficiency
  - If a normal time slot consists of 6 trailing bits, 8.25 guard bits, 26 training bits, and 2 traffic bursts of 58 bits of data, find the frame efficiency

Solution 3.1/3.2

1. Bit duration : Tb = 1/270.833 Kbps = 3.692 microsecs
2. Slot duration = 156.25* 3.692 =0.577 milliseconds
3. Frame duration = 8 * 0.577 = 4.615 milli secs
4. A user has to wait for a duration of a frame before it gets a chance for its next transmission

Solution for 3.2

1. A time slot = 6+8.25+26+2*58 = 156.25 bits
2. A frame has 8* 156.25 = 1250 bits
3. Number of overhead bits per farme = 8 *(6+8.25+26) =322 bits
4. Frame efficiency = (1250 -322)/1250 = 74.24 %

Spread Spectrum Multiple Access

- Frequency Hopped Multiple Access(FHMA)
- Code Division Multiple Access
- Hybrid Spread Spectrum Techniques

Spread Spectrum multiple access (SSMA)

Spread Spectrum multiple access (SSMA) uses signals which have a transmission bandwidth that is several orders of magnitude greater than the minimum required RF bandwidth. A PN sequence converts a narrowband signal to a wideband noise-like signal before transmission.

Advantage:

1. Immune to multipath interference and robust multiple access capability.
2. Efficient in a multiple user environment

Two main types of SSMA:

1. Frequency hopped multiple access (FH)
2. Direct sequence multiple access (DS)

   Code division multiple access(CDMA)

Frequency Hopped Multiple Access (FHMA)

FHMA is a digital multiple access system in which the carrier frequencies of the individual users are varied in a pseudorandom fashion within a wideband channel.

- In a FH transmitter:

1. The digital data is broken into uniform sized bursts which are transmitted on different carrier frequencies.
2. The instantaneous bandwidth of any one transmission burst is much smaller than the total spread bandwidth.
3. The pseudorandom change of the carrier frequencies of the user randomizes the occupancy of a specific channel at any given time.

Frequency Hopped Multiple Access (FHMA)

In FH receiver:

1. A locally generated PN code is used to synchronize the receivers instantaneous frequency with that of the transmitter.
2. At any given point in time, a frequency hopped signal only occupies a single, relatively narrow channel since narrowband FM or FSK is used.
3. FHMA systems often employ energy efficient constant envelope modulation.
4. Linearity is not an issue, and the power of multiple users at the receiver does not degrade FHMA performance.

The difference between FHMA and FDMA

The difference between FHMA and FDMA is that the frequency hopped signal changes channels at rapid interval.

If the rate of change of the carrier frequency is greater than the symbol rate, it is referred to as a fast frequency hopping. (FDMA)

If the channel changes at a rate less than or equal to the symbol rate, it is called slow frequency hopping system.

Advantage of FH system

1. A frequency hopped system provides a level of security, since an unintended receiver that does not know the pseudorandom sequence of frequency slots must retune rapidly to search for the signal it wishes to intercept.
2. FH signal is somewhat immune to fading, since error control coding and interleaving can be used to protect the frequency hopped signal against deep fades which may occasionally occur during the hopping sequence.

Code Division Multiple Access CDMA

- The spreading signal is a pseudo-noise code sequence that has a chip rate which is orders of magnitudes greater than the data rate of the message.
- All users in CDMA system, use the same carrier frequency and may transmit simultaneously.
- In CDMA, the narrowband message signal is multiplied by a very large bandwidth signal called the spreading signal.
- Each user has its own pseudorandom codeword which is approximately orthogonal to all other codewords.
- The receiver performs a time correlation operation to detect only the specific desired codeword.

SSMA

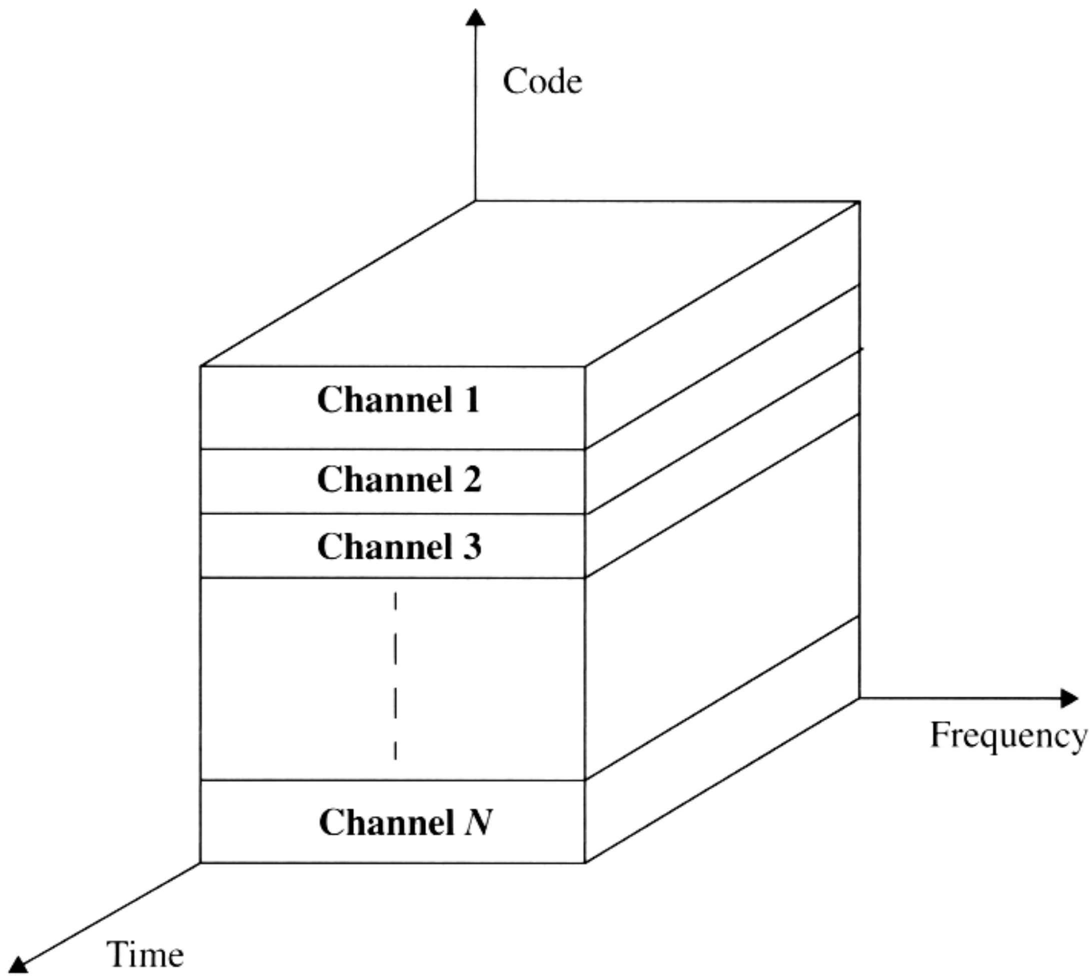


Figure 9.5 Spread spectrum multiple access in which each channel is assigned a unique PN code which is orthogonal or approximately orthogonal to PN codes used by other users.

CDMA

The near-far problem

- when many mobile users share the same channel, the strongest received mobile signal will capture the demodulator at a base station.
- In CDMA, stronger received signal levels raise the noise floors at the base station demodulators for the weaker signals, thereby decreasing the probability that weaker signals will be received.

Solution: power control

- Power control is provided by each base station in a cellular system and assures that each mobile within the base station coverage area provides the same signal level to the base station receiver. This solves the problem of a near by subscriber over powering the base station
- Power control is implemented at the base station by rapidly sampling the radio signal strength indicator levels of each mobile and then sending a power change command over the forward radio link.

The features of CDMA

1. Many users of a CDMA system share the same frequency.
2. CDMA has a soft capacity. Increasing the number of users in a CDMA system raises the noise floor in a linear manner.
3. Multipath fading may be substantially reduced, because the signal is spread over a large bandwidth. If the spread spectrum BW greater than the coherence BW of the channel, the inherent freq diversty will mitigate the efefcts of small scale fading.
4. Channel data rates are very high in CDMA system. A Chip (symbol duration) is usually much smaller than the delay spread. The PN sequences have low autocorrelation, multipath which is delayed by more than a chip will appear as noise. A rake receiver can be used to improve reception by collecting time delayed versions of the signal

The features of CDMA

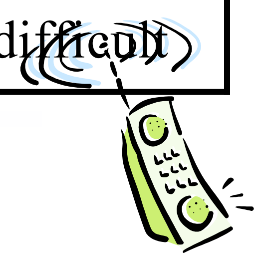
- Macroscopic Spatial Diversity
  - CDMA uses co-channel cells it can use macroscopic spatial diversity to provide soft handoff. Soft handoff is performed by the MSC, which can monitor the user from 2 or more base stations. MSC then chooses the best version of the signal at any time.
- Self Jamming
  - It arises because the PN codes of the users are not exact orthogonal. Hence in despreading of a specific code, there may be non-zero contributions from other users, which influences the receiver decision process
- The near-far problem occurs in CDMA system.

Comparison of DS and FH system

	DS	FH
Bandwidth	PN sequence clock rate or chip rate	The tuning range of frequencies
Synchronization	Very crucial	Less critical
Spectrum	Very wide	narrow
Near-far problem	More likely to occur	Less likely to occur

Comparison of FDMA, TDMA, CDMA

Feature	FDMA	TDMA	CDMA
High carrier frequency stability	Required	Not necessary	Not necessary
Timing/synchronization	Not required	Required	Required
Near-far problem	No	No	Yes,power control tech.
Variable transmission rate	Difficult	Easy	Easy
Fading mitigation	Equalizer not needed	Equalizer may be needed	RAKE receiver possible
Power monitoring	Difficult	Easy	Easy
Zone size	Any size	Any size	Large size difficult



Hybrid Spread Spectrum Techniques

1. Hybrid FDMA/CDMA(FCDMA)
2. Hybrid Direct Sequence/Frequency Hopped Multiple Access(DS/FHMA)
3. Time Division CDMA(TCDMA)
4. Time Division Frequency Hopping(TDFH)

Hybrid FDMA/CDMA(FCDMA)

The available wideband spectrum is divided into a number of subspectras with smaller bandwidths. Each of these smaller subchannels becomes a narrowband CDMA system having processing gain lower than the original CDMA system.

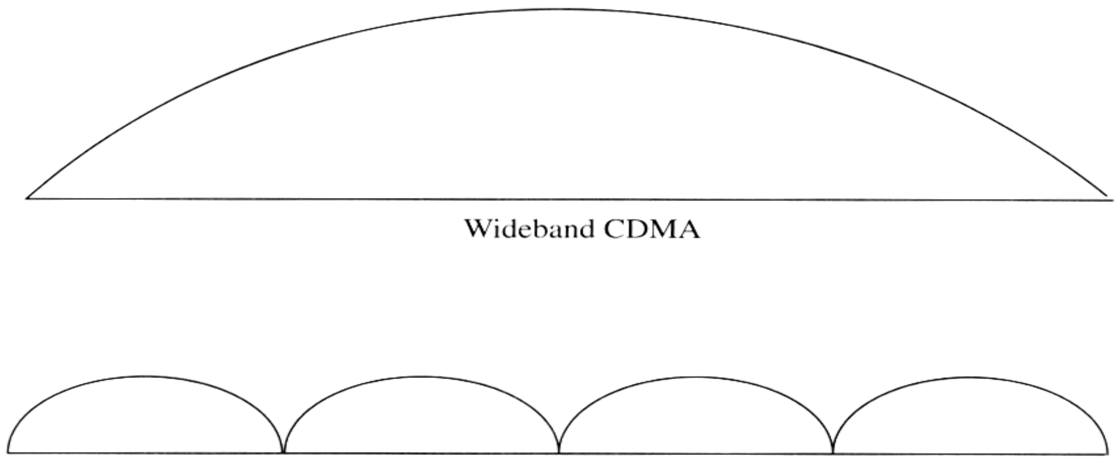


Figure 9.6 Spectrum of wideband CDMA compared to the spectrum of a hybrid, frequency division, direct sequence multiple access.

Advantage: the required bandwidth need not be contiguous and different users and be allotted different subspectrum bandwidths depending on their requirement.

Hybrid Direct Sequence/Frequency Hopped Multiple Access(DS/FHMA)

This technique consists of a direct sequence modulated signal whose center frequency is made to hop periodically in a pseudorandom fashion.

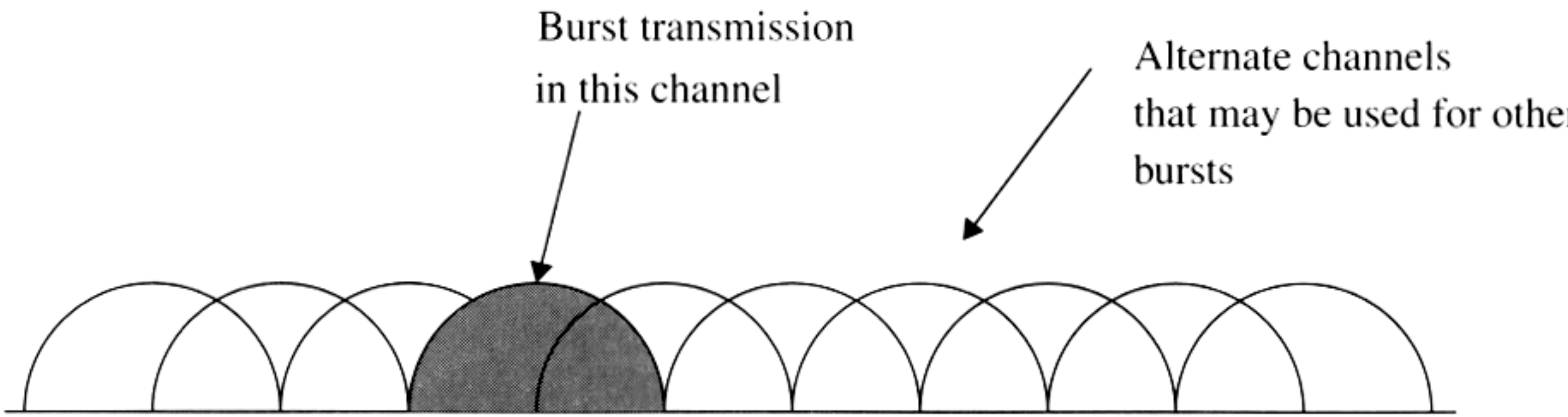


Figure 9.7 Frequency spectrum of a hybrid FH/DS system.

Advantage: they avoid the near-far effect.

Disadvantage: they are not adaptable to the soft handoff process.

Time Division Frequency Hopping (TDFH)

- Time Division Frequency Hopping(TDFH)
- The subscriber can hop to a new frequency at the start of a new TDMA frame. In GSM standard, hopping sequence is predefined and the subscriber is allowed to hop only on certain frequencies which are assigned to a cell.
- Advantage:
  - Avoiding a severe fade or erasure event on a particular channel.
  - Avoiding the co-channel interference problems between neighboring cells if two interfering base station transmitters are made to transmit on different frequencies at different times.

Space Division Multiple Access(SDMA)

SDMA controls the radiated energy for each user in space. From Fig 9.8., we see that different areas covered by the antenna beam may be served by the same frequency or different frequencies.

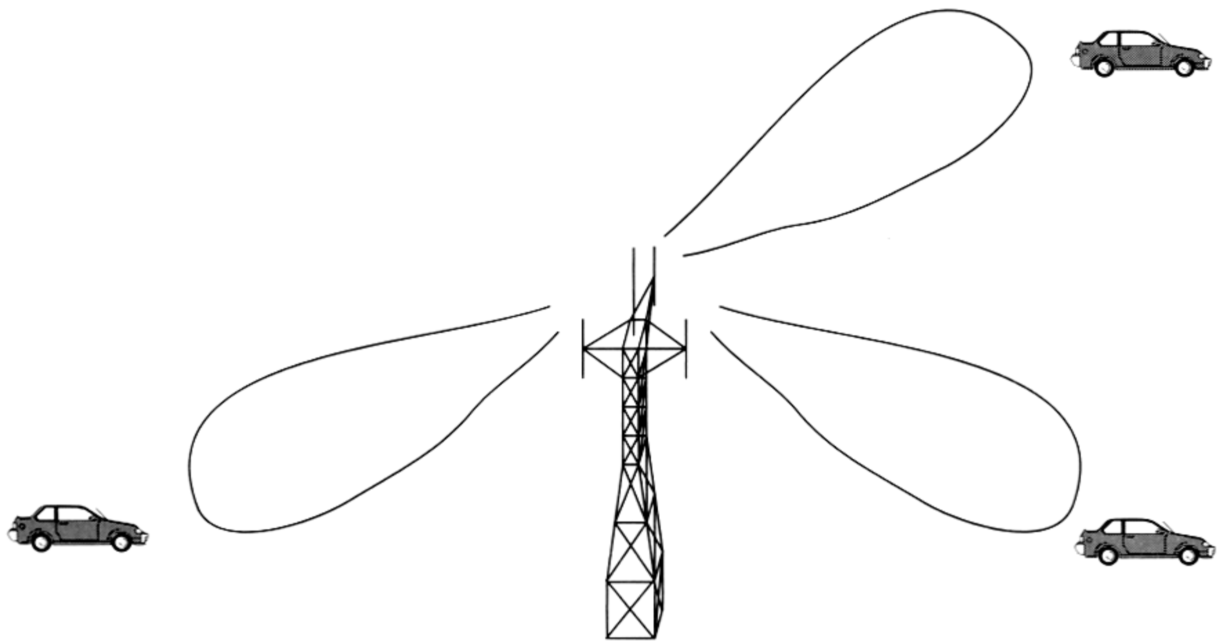


Figure 9.8 A spatially filtered base station antenna serving different users by using spot beams.

Space Division Multiple Access

- Sectorized antennas may be thought of as a primitive application of SDMA. In the future, adaptive antennas will likely be used to simultaneously steer energy in the direction of many users at once and appear to be best suited for TDMA and CDMA base station architectures.

Dynamic Channel Allocation Parameters

- Station Model.
  - *N* independent stations, each acting as a Poisson Process for the purpose protocol analysis
- Single Channel Assumption.
  - A single channel is available for all communication.
- Collision Assumption.
  - If transmitted frames overlap in time, the resulting signal is garbled.
- Transmission Discipline:
  - Continuous time
    - Frames can be transmitted at any time
  - Slotted time
    - Frames can be transmitted at particular time points
- Sensing capability:
  - Station cannot sense the channel before trying to use it.
  - Stations can tell if the channel is in use before trying to use it

Packet Radio

In *packet radio* **(PR)** access techniques, many subscribers attempt to access a single channel in an uncoordinated (or minimally coordinated) manner. Transmission is done by using bursts of data. Collisions from the simultaneous transmissions of multiple transmitters are detected at the base station receiver, in which case an *ACK* or *NACK* signal is broadcast by the base station to alert the desired user (and all other users) of received transmission

Packet radio multiple access is very easy to implement, but has low spectral efficiency and may induce delays. The subscribers use a contention technique to transmit on a common channel.

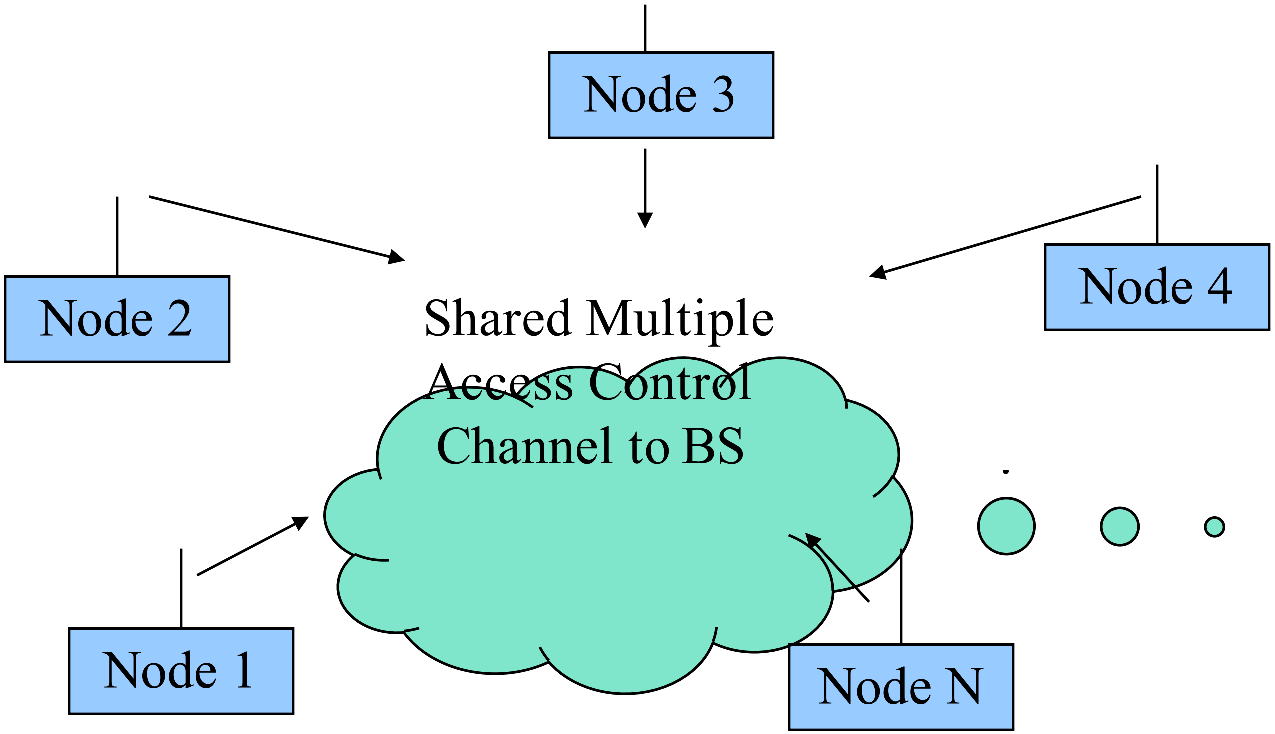
contention techniques are

- ALOHA
- Slotted ALOHA
- CSMA
  - ✓ Persistent CSMA
  - ✓ Nonpersistant

Multiple access control channels

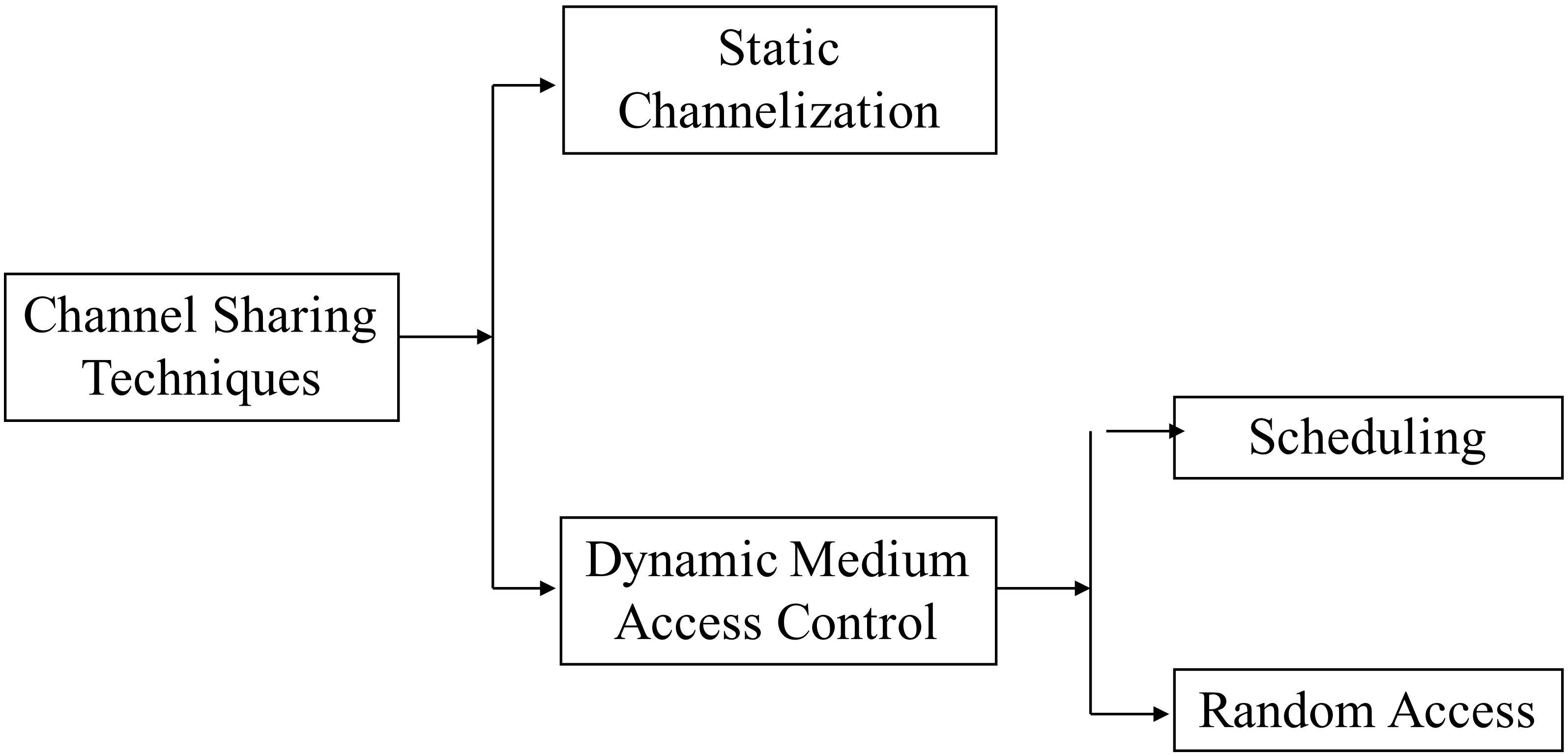
Each node is attached to a transmitter/receiver which communicates via a channel shared by other nodes

Transmission from any node is received by other nodes

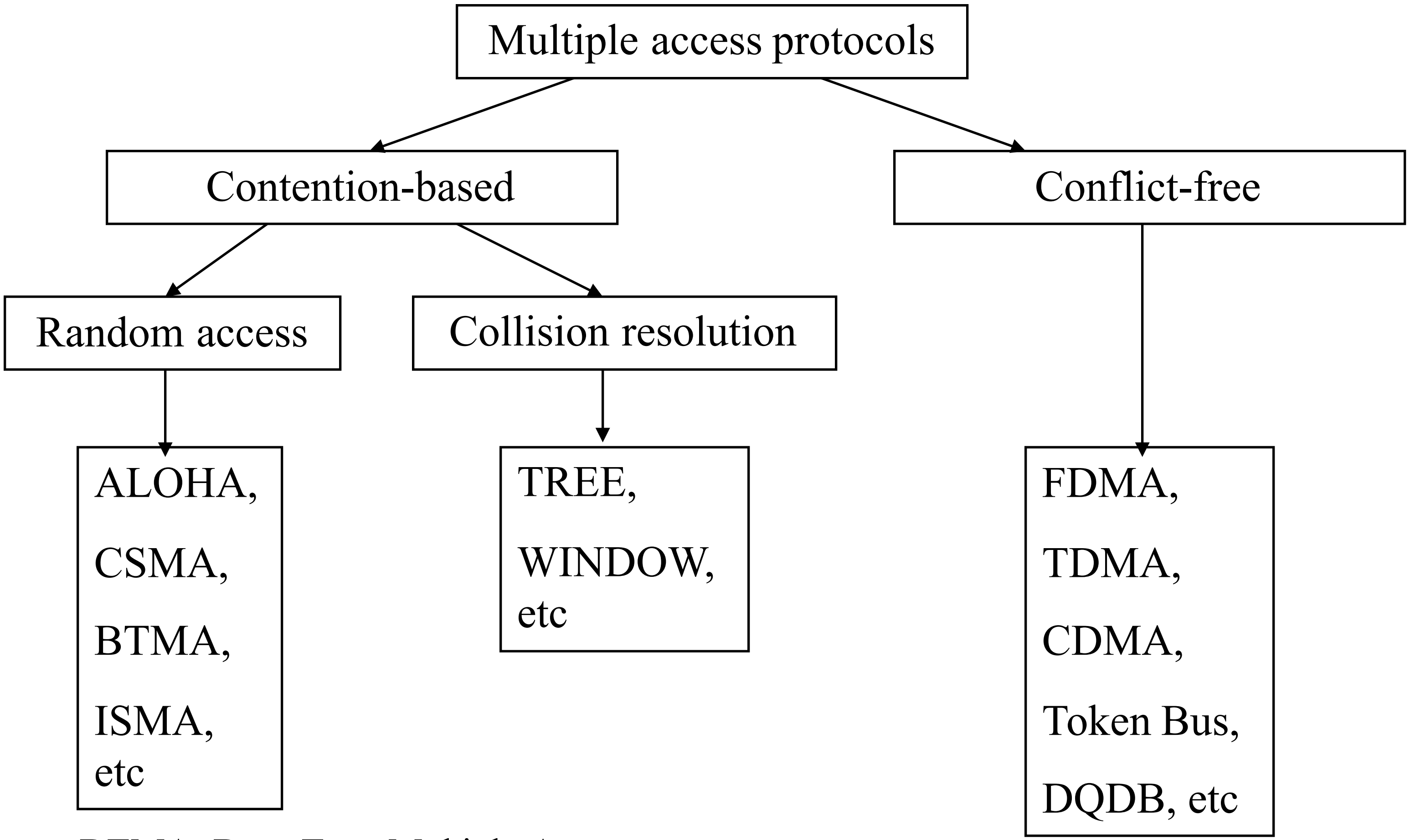


- Multiple access issues
  - If more than one node transmit at a time on the control channel to BS, a collision occurs
  - How to determine which node can transmit to BS?
- Multiple access protocols
  - Solving multiple access issues
  - Different types:
    - Contention protocols resolve a collision after it occurs. These protocols execute a collision resolution protocol after each collision
    - Collision-free protocols (e.g., a bit-map protocol and binary countdown) ensure that a collision can never occur.

Channel Sharing Techniques



Classification of Multiple Access Protocols



BTMA: Busy Tone Multiple Access
ISMA: Internet Streaming Media Alliance

DQDB: Distributed Queue Dual Bus

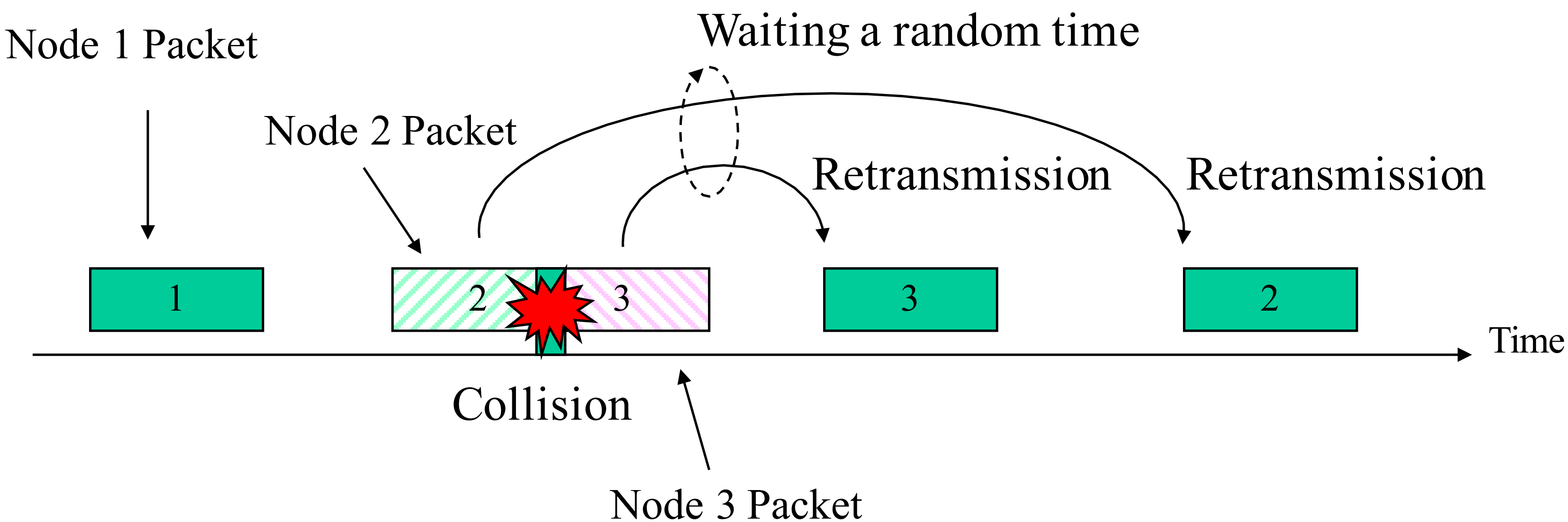
Contention Protocols

- **ALOHA**
  - Developed in the 1970s for a packet radio network by Hawaii University.
  - Whenever a station has a data, it transmits. Sender finds out whether transmission was successful or experienced a collision by listening to the broadcast from the destination station. Sender retransmits after some random time if there is a collision.
- **Slotted ALOHA**
  - Improvement: Time is slotted and a packet can only be transmitted at the beginning of one slot. Thus, it can reduce the collision duration.

Contention Protocols (Cont’d)

- **CSMA** (Carrier Sense Multiple Access)
  - Improvement: Start transmission only if no transmission is ongoing
- **CSMA/CD** (CSMA with Collision Detection)
  - Improvement: Stop ongoing transmission if a collision is detected
- **CSMA/CA** (CSMA with Collision Avoidance)
  - Improvement: Wait a random time and try again when carrier is quiet. If still quiet, then transmit
- **CSMA/CA with ACK**
- **CSMA/CA with RTS/CTS**

ALOHA



Collision mechanism in ALOHA

Throughput of ALOHA

- The probability that n packets arrive in two packets time is given by

$$P(n) = \frac{(2G)^n e^{-2G}}{n!}$$

where G is traffic load.

- The probability $P(0)$ that a packet is successfully received without collision is calculated by letting $n=0$ in the above equation. We get

$$P(0) = e^{-2G}$$

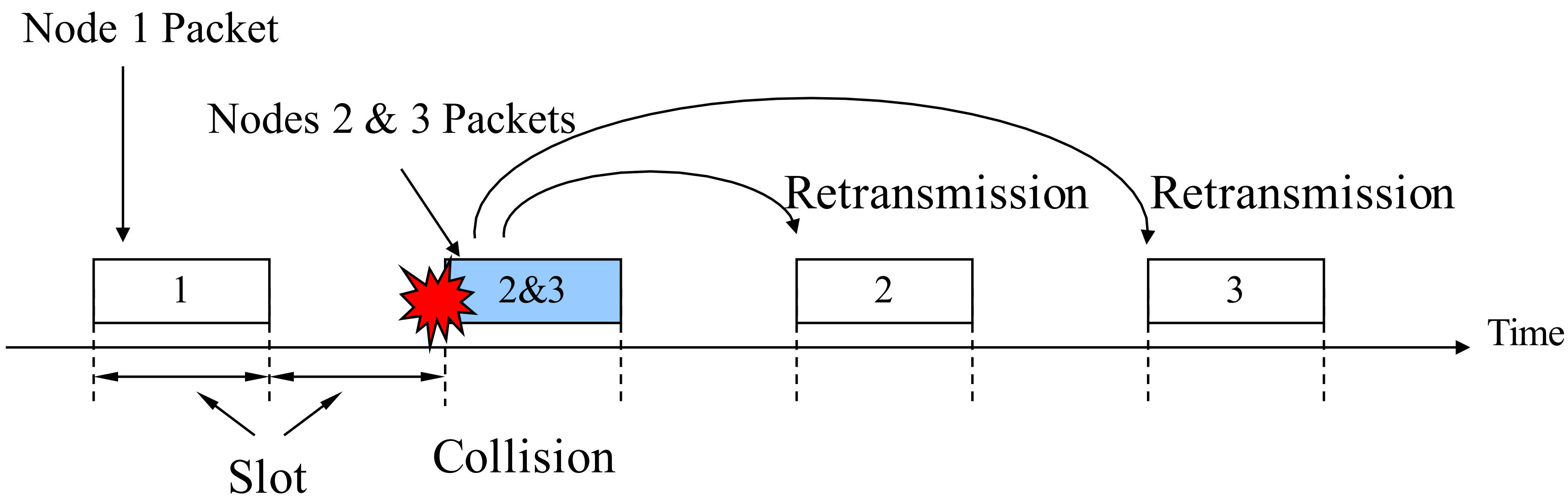
- We can calculate throughput S with a traffic load G as follows:

$$S = G \cdot P(0) = G \cdot e^{-2G}$$

- The Maximum throughput of ALOHA is

$$S_{\max} = \frac{1}{2e} \approx 0.184$$

Slotted ALOHA



Collision mechanism in slotted ALOHA

Throughput of Slotted ALOHA

- The probability of no collision is given by

$$P(0) = e^{-G}$$

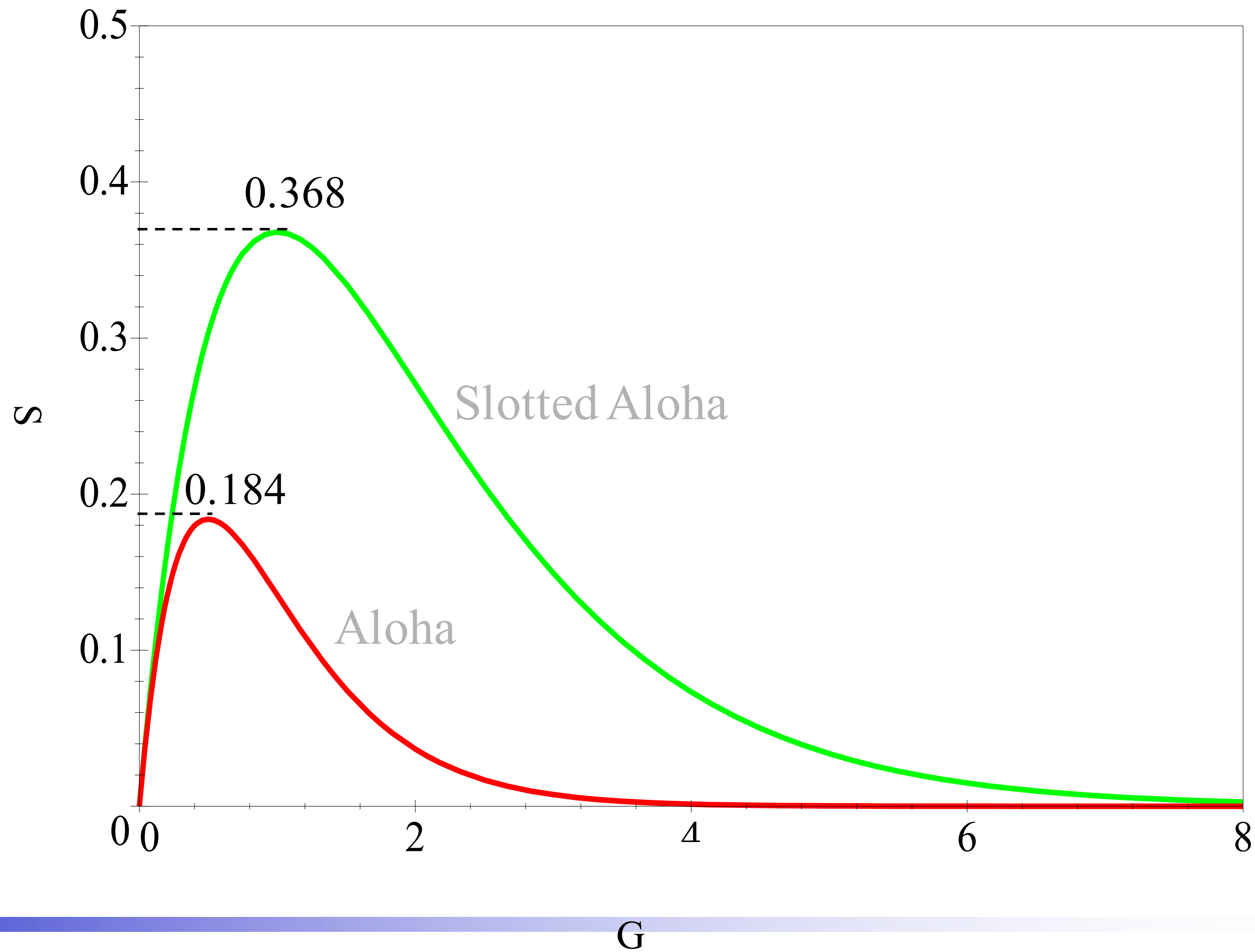
- The throughput S is

$$S = G \cdot P(0) = G \cdot e^{-G}$$

- The Maximum throughput of slotted ALOHA is

$$S_{\max} = \frac{1}{e} \approx 0.368$$

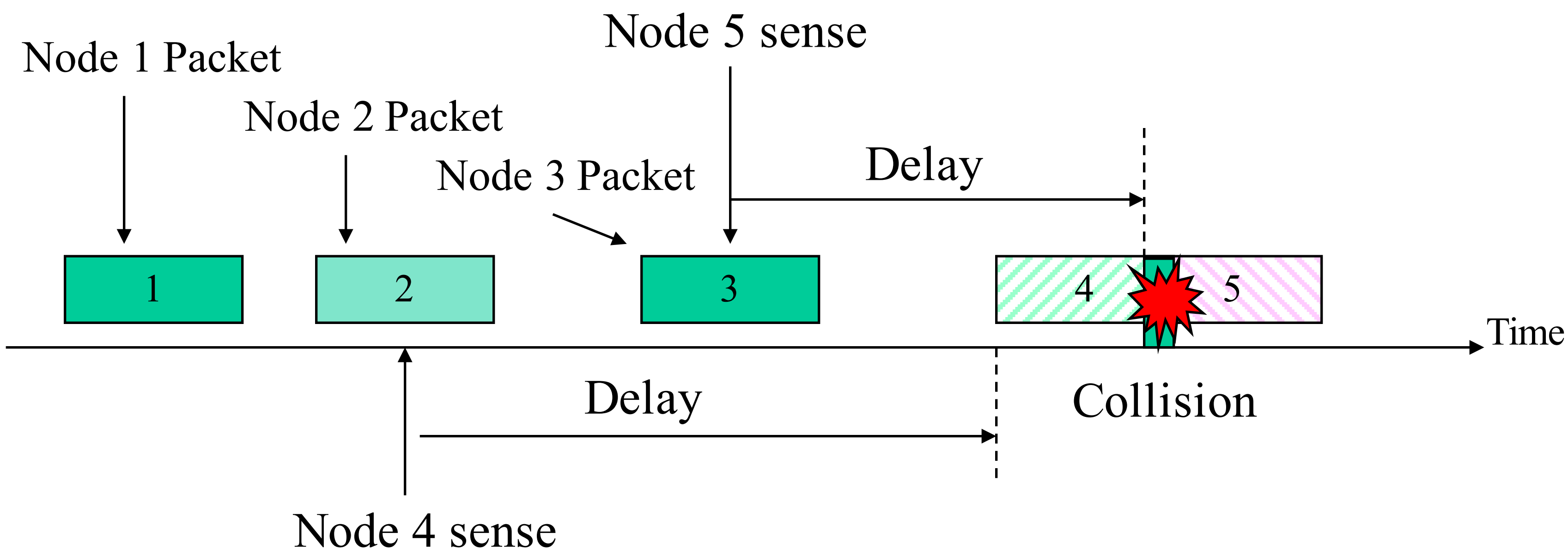
Throughput



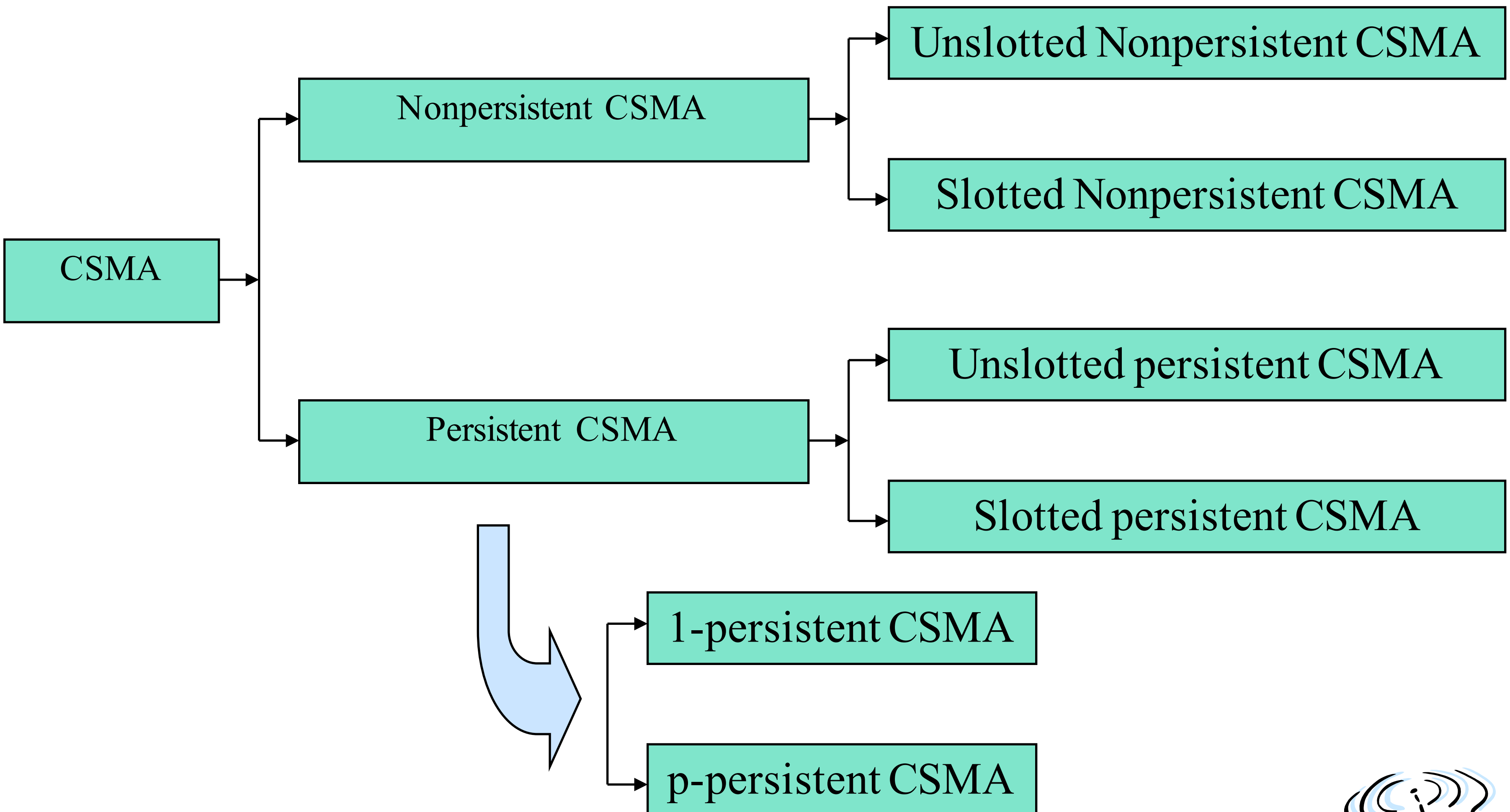
CSMA (Carrier Sense Multiple Access)

- Max throughput achievable by slotted ALOHA is 0.368.
- CSMA gives improved throughput compared to Aloha protocols.
- Listens to the channel before transmitting a packet (avoid avoidable collisions).

Collision Mechanism in CSMA



Kinds of CSMA



Nonpersistent/x-persistent CSMA Protocols

- Nonpersistent CSMA Protocol:

Step 1: If the medium is idle, transmit immediately

Step 2: If the medium is busy, wait a random amount of time and repeat **Step 1**

- Random backoff reduces probability of collisions
- Waste idle time if the backoff time is too long

- 1-persistent CSMA Protocol:

Step 1: If the medium is idle, transmit immediately

Step 2: If the medium is busy, continue to listen until medium becomes idle, and then transmit immediately

- There will always be a collision if two nodes want to retransmit (usually you stop transmission attempts after few tries)

Nonpersistent/x-persistent CSMA Protocols

- p-persistent CSMA Protocol:

Step 1: If the medium is idle, transmit with probability p, and delay for worst case propagation delay for one packet with probability (1-p)

Step 2: If the medium is busy, continue to listen until medium becomes idle, then go to **Step 1**

Step 3: If transmission is delayed by one time slot, continue with **Step 1**

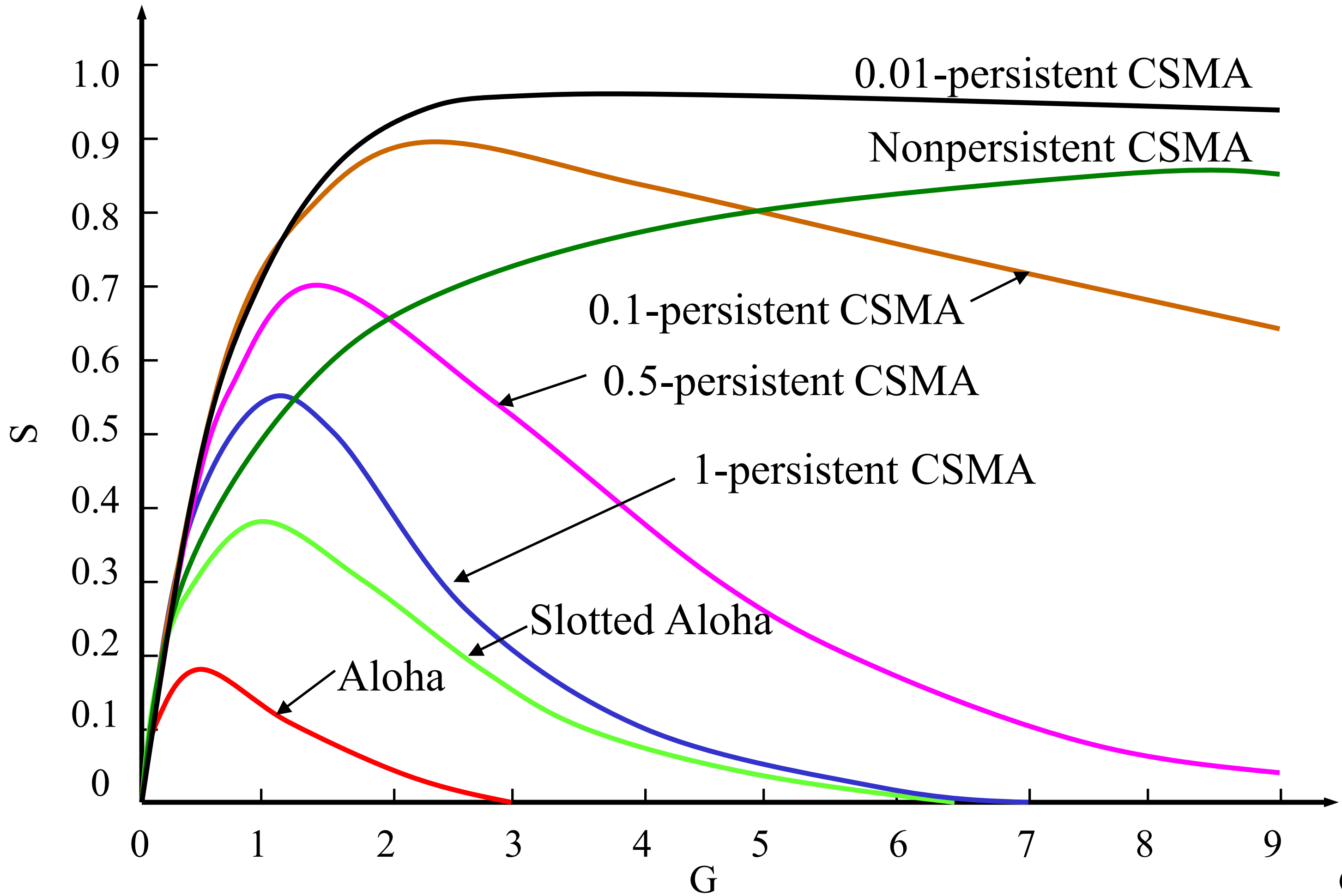
- A good tradeoff between nonpersistent and 1-persistent CSMA

How to Select Probability *p* ?

- Assume that *N* nodes have a packet to send and the medium is busy
- *Then, Np* is the expected number of nodes that will attempt to transmit once the medium becomes idle
- If $Np > 1$, then a collision is expected to occur

Therefore, network must make sure that $Np < 1$ to avoid collision, where *N* is the maximum number of nodes that can be active at a time

Throughput



0.01-persistent CSMA
Nonpersistent CSMA
0.1-persistent CSMA
0.5-persistent CSMA
1-persistent CSMA
Slotted Aloha
Aloha
S
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
G
0
1
2
3
4
5
6
7
8
9

CSMA/CD (CSMA with Collision Detection)

- In CSMA, if 2 terminals begin sending packet at the same time, each will transmit its complete packet (although collision is taking place).
- Wasting medium for an entire packet time.
- CSMA/CD

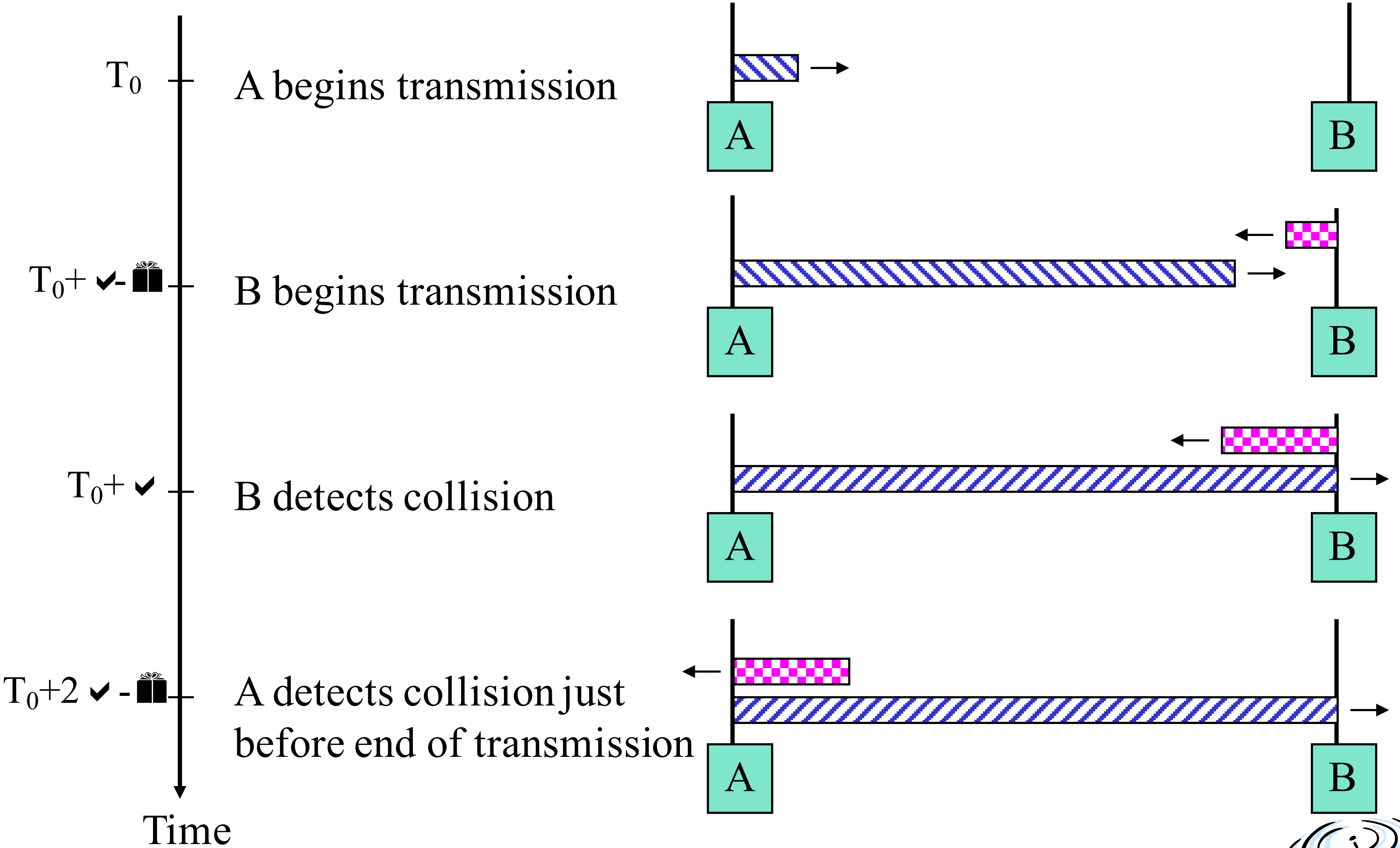
  Step 1: If the medium is idle, transmit

  Step 2: If the medium is busy, continue to listen until the channel is idle then transmit

  Step 3: If a collision is detected during transmission, cease transmitting

  Step 4: Wait a random amount of time and repeats the same algorithm

CSMA/CD (Cont'd)

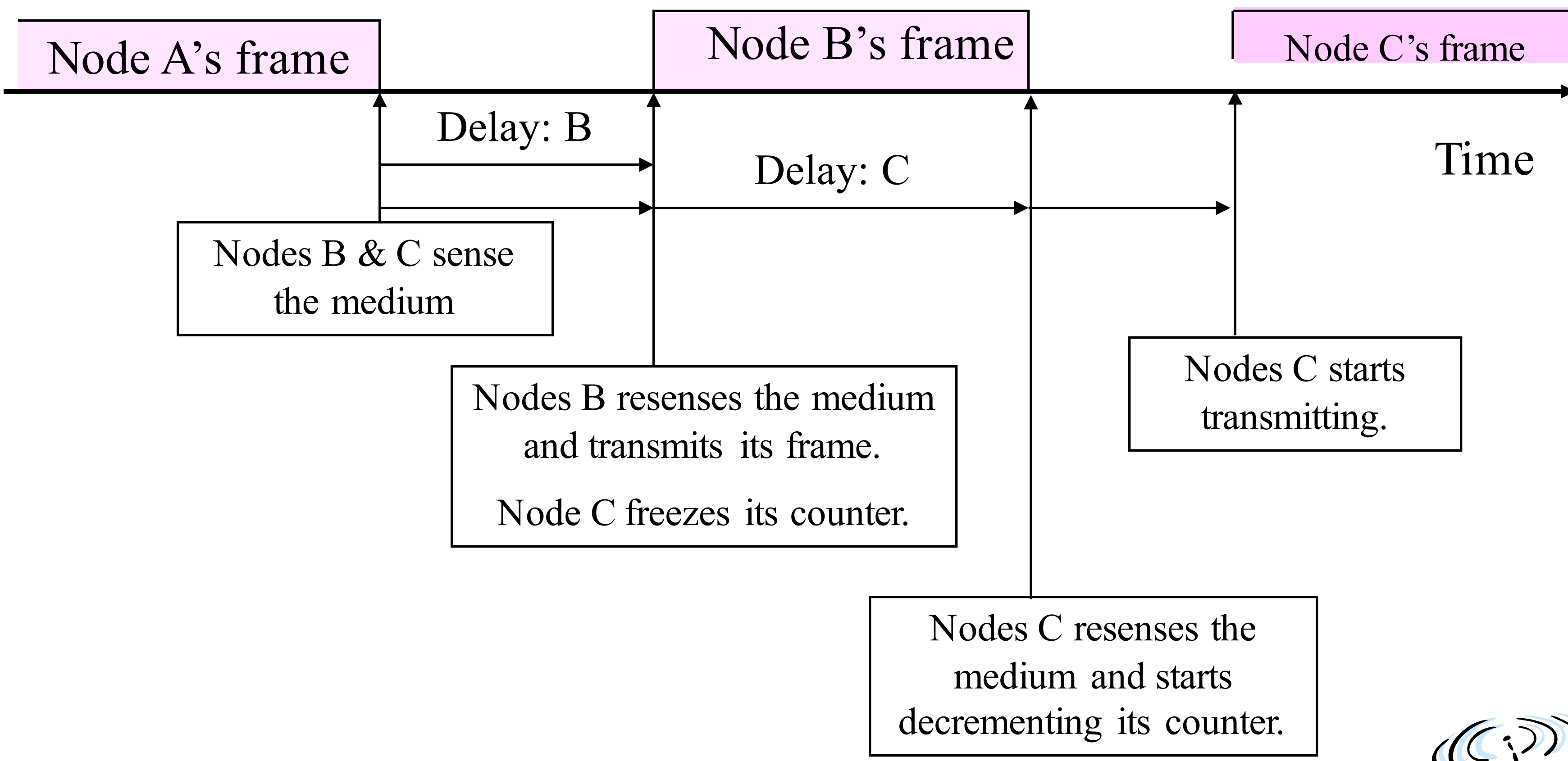


(✔ is the propagation time)

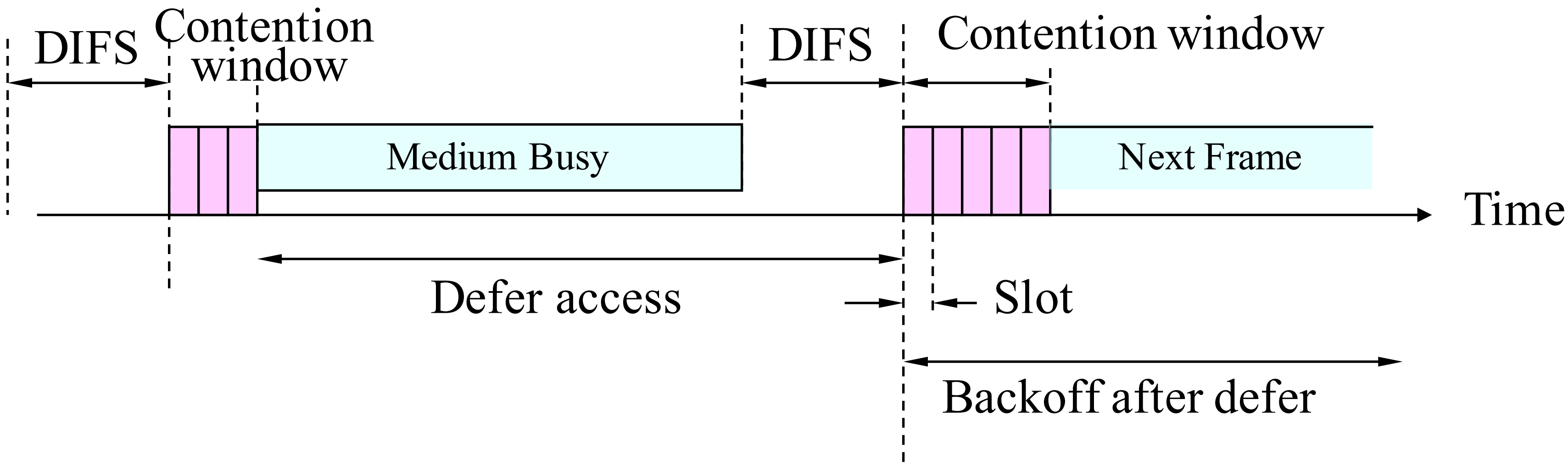
CSMA/CA (CSMA with collision Avoidance)

- All terminals listen to the same medium as CSMA/CD.
- Terminal ready to transmit senses the medium.
- If medium is busy it waits until the end of current transmission.
- It again waits for an additional predetermined time period DIFS (Distributed inter frame Space).
- Then picks up a random number of slots (the initial value of backoff counter) within a contention window to wait before transmitting its frame.
- If there are transmissions by other terminals during this time period (backoff time), the terminal freezes its counter.
- It resumes count down after other terminals finish transmission + DIFS. The terminal can start its transmission when the counter reaches to zero.

CSMA/CA (Cont'd)



CSMA/CA Explained

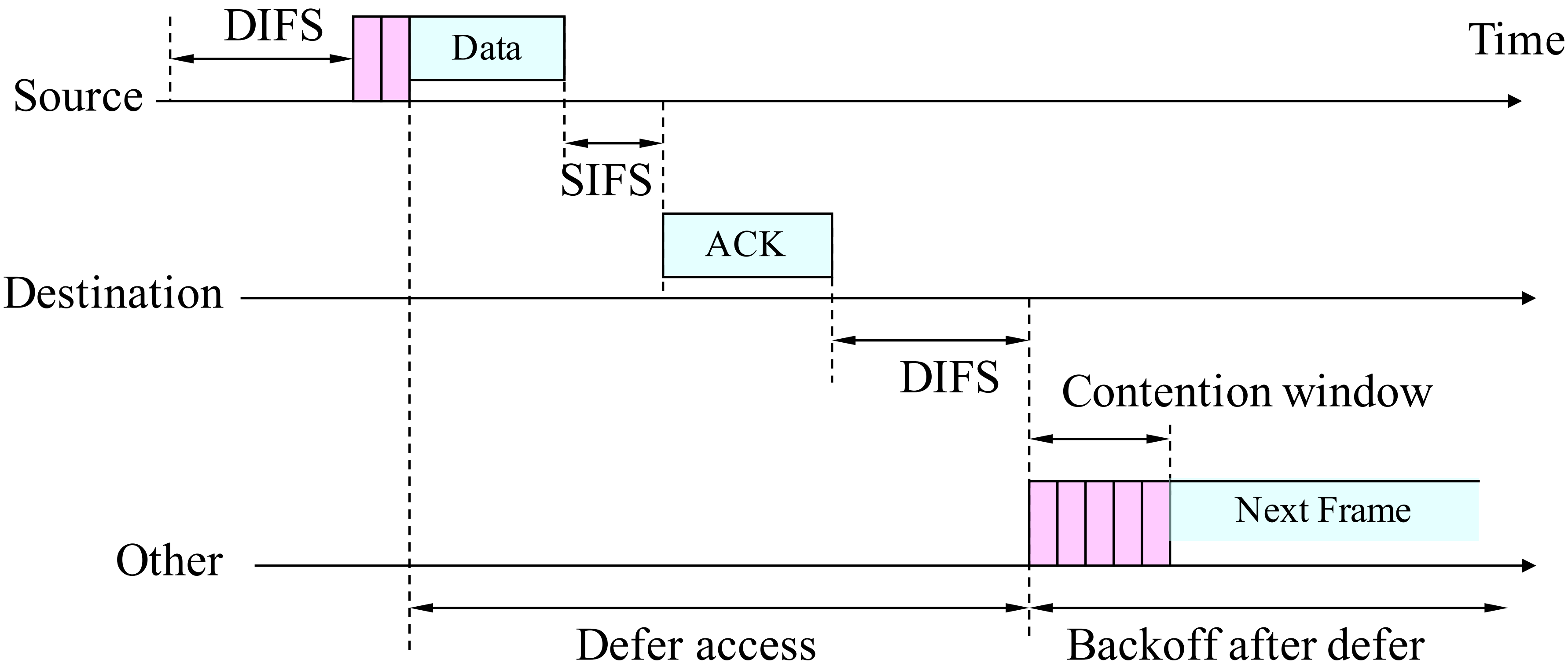


DIFS – Distributed Inter Frame Spacing

CSMA/CA with ACK

- Immediate Acknowledgements from receiver upon reception of data frame without any need for sensing the medium.
- ACK frame transmitted after time interval SIFS (*Short Inter-Frame Space*) (*SIFS* < *DIFS*)
- Receiver transmits ACK without sensing the medium.
- If ACK is lost, retransmission done.

CSMA/CA/ACK

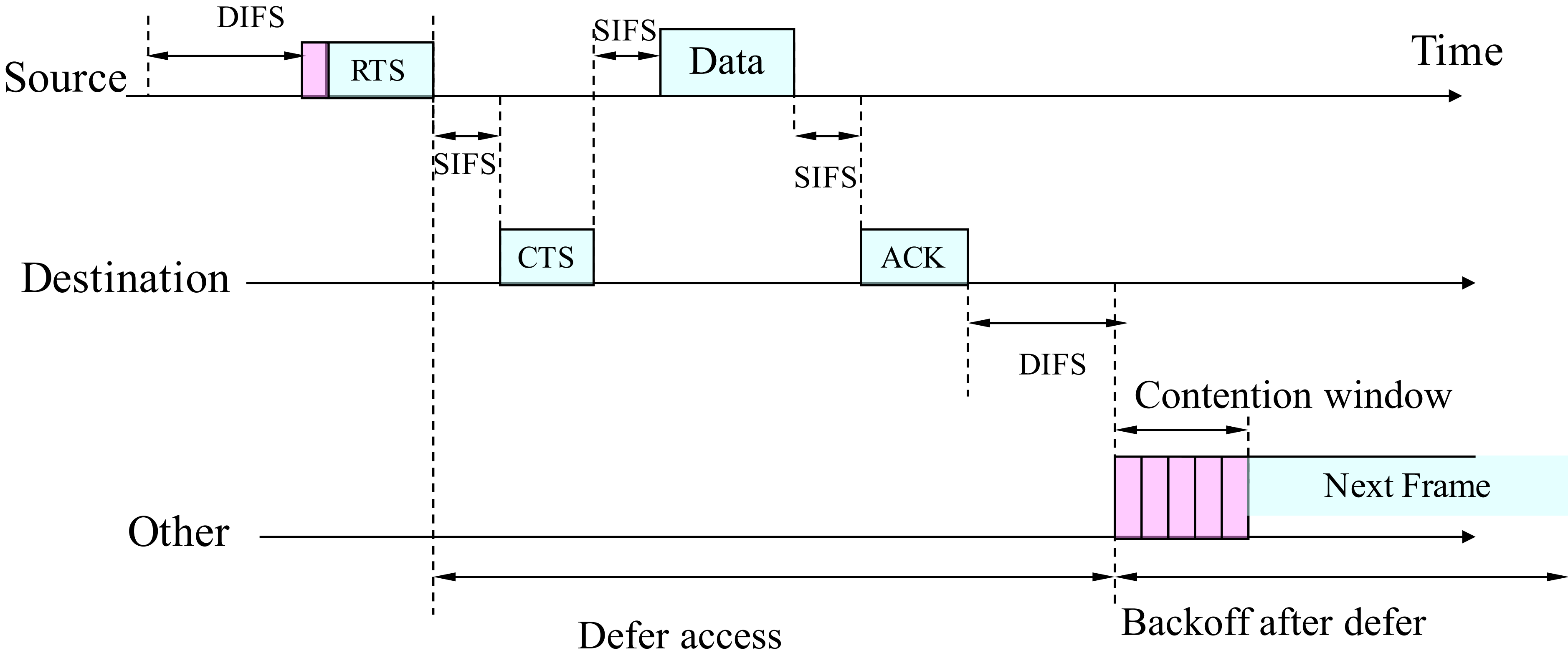


SIFS – Short Inter Frame Spacing

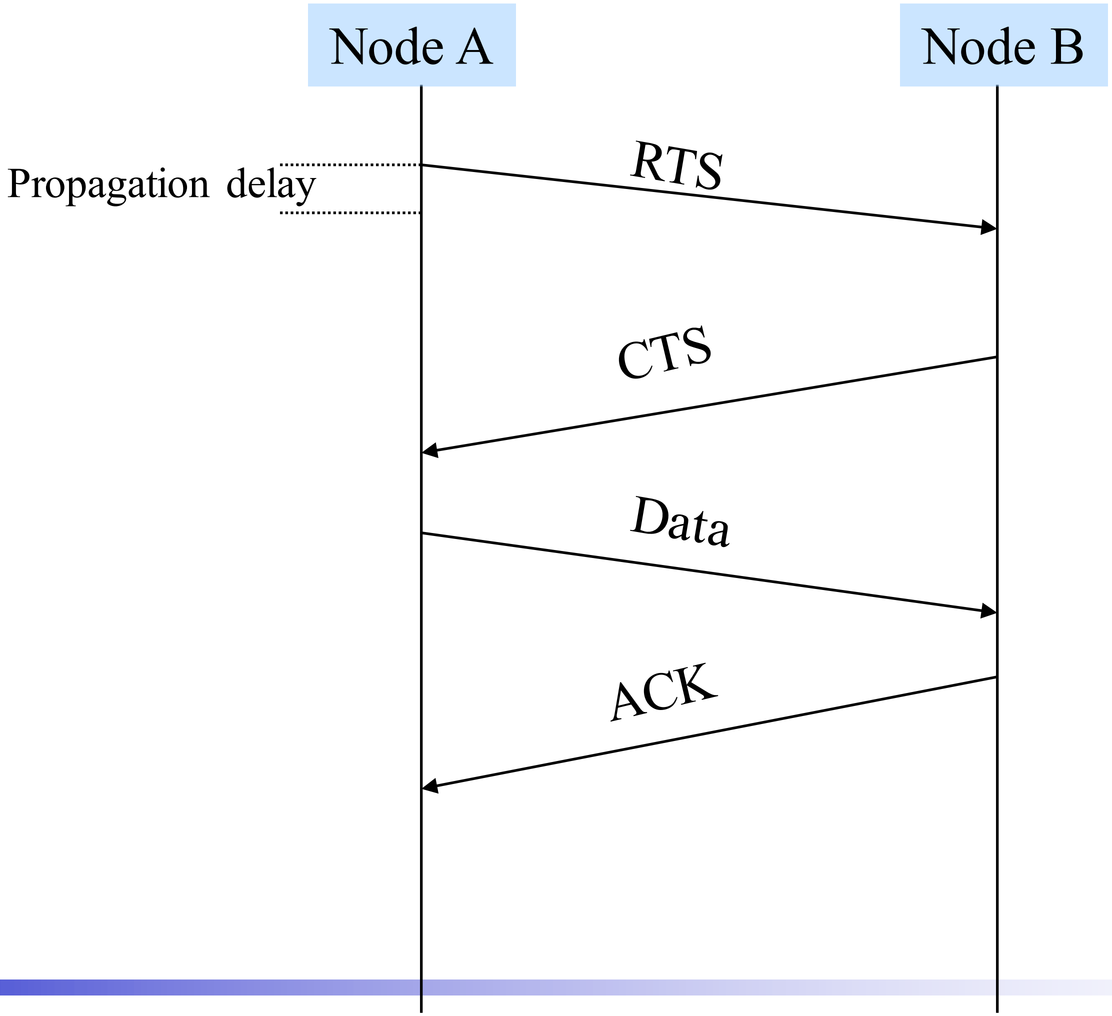
CSMA/CA with RTS/CTS

- Transmitter sends an RTS (request to send) after medium has been idle for time interval more than DIFS.
- Receiver responds with CTS (clear to send) after medium has been idle for SIFS.
- Then Data is exchanged.
- RTS/CTS is used for reserving channel for data transmission so that the collision can only occur in control message.

CSMA/CA with RTS/CTS (Cont'd)



RTS/CTS



Throughput expression

Protocol	Throughput
Pure ALOHA	$S = Ge^{-2G}$
Slotted ALOHA	$S = Ge^{-G}$
Unslotted 1-persistent CSMA	$S = \dfrac{G\left[1 + G + aG\left(1 + G + aG/2\right)\right]e^{-G(1+2a)}}{G\left(1+2a\right) - \left(1 - e^{-aG}\right) + \left(1 + aG\right)e^{-G(1+a)}}$
Slotted 1-persistent CSMA	$S = \dfrac{G\left[1 + a - e^{-aG}\right]e^{-G(1+a)}}{\left(1+a\right)\left(1 - e^{-aG}\right) + ae^{-G(1+a)}}$
Unslotted nonpersistent CSMA	$S = \dfrac{Ge^{-aG}}{G\left(1+2a\right) + e^{-aG}}$
Slotted nonpersistent CSMA	$S = \dfrac{aGe^{-aG}}{1 - e^{-aG} + a}$

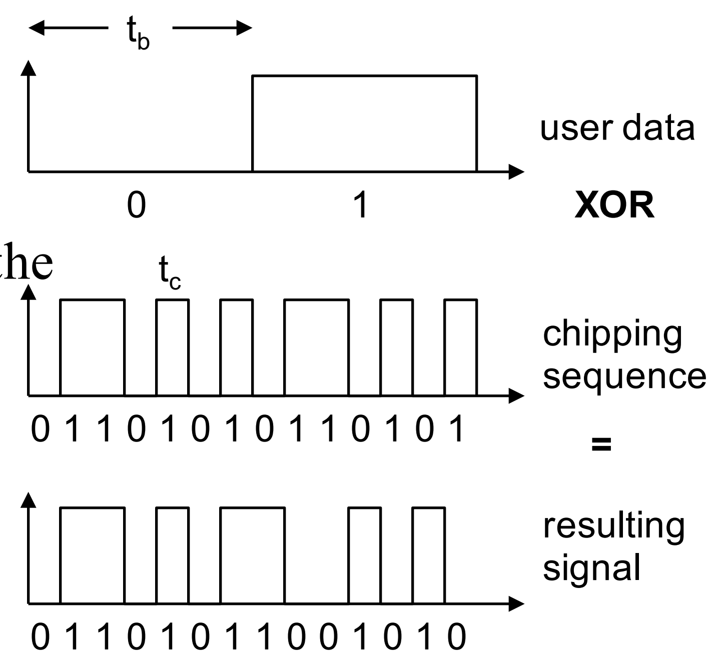
Some medium access control mechanisms for wireless

- SDMA
- TDMA
  - Fixed
    - Used in GSM
  - Aloha
    - Pure
    - Slotted
  - CSMA
    - Non-persistent
    - p-persistent
    - CSMA/CA
      - Used in 802.11 (mandatory)
  - Reservations DAMA
  - Multiple Access with Collision Avoidance
    - Copes with hidden and exposed terminal
    - RTS/CTS
    - Used in 802.11 (optional)
    - MACAW
    - MACA-BI
    - FAMA
      - CARMA
  - Polling
    - Used in 802.11 (optional)
- FDMA
  - Fixed
    - Used in GSM
  - FHSS
    - Used in Bluetooth
- CDMA
  - DSSS
    - Used in UMTS

FHSS: Frequency-Hopping Spread Spectrum
DSSS: Direct Sequence Spread Spectrum
CSMA: Carrier Sense Multiple Access
CA: Collision Avoidance
DAMA: Demand-Assigned Multiple Access
MACA-BI: MACA by invitation
FAMA: Floor Acquisition Multiple Access
CARMA: Collision Avoidance and Resolution Multiple Access

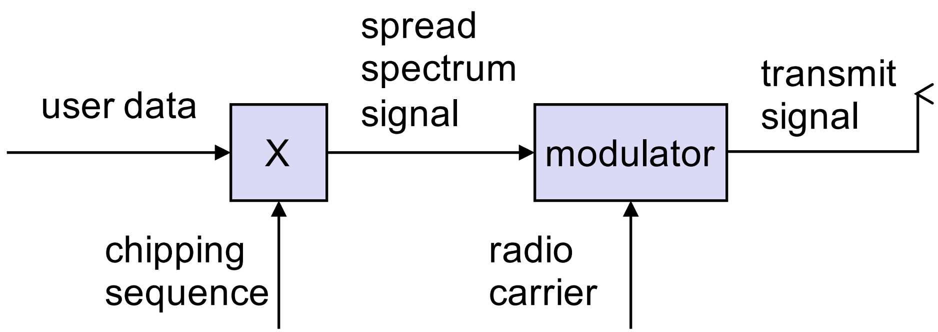
Direct Sequence Spread Spectrum (DSSS) (1/2)

- XOR of the signal with pseudo-random number (chipping sequence)
  - many chips per bit (e.g., 128) result in higher bandwidth of the signal
- Advantages
  - reduces frequency selective fading
  - in cellular networks
    - neighboring base stations can use the same frequency range
    - neighboring base stations can detect and recover the signal
    - ➔ enables *soft handover*
- Disadvantages
  - precise power control necessary
  - complexity of the receiver

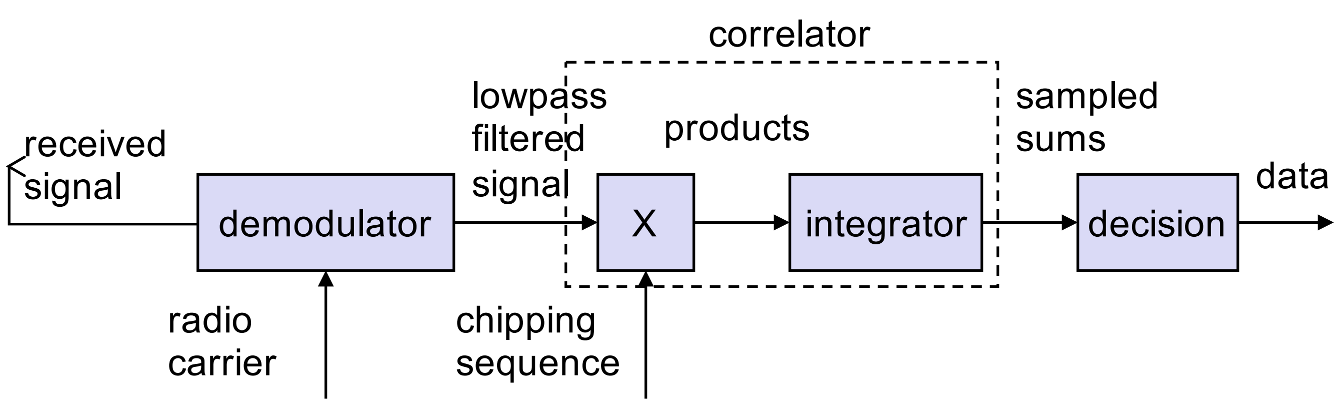


t_b: bit period
t_c: chip period

Direct Sequence Spread Spectrum (DSSS) (2/2)



transmitter

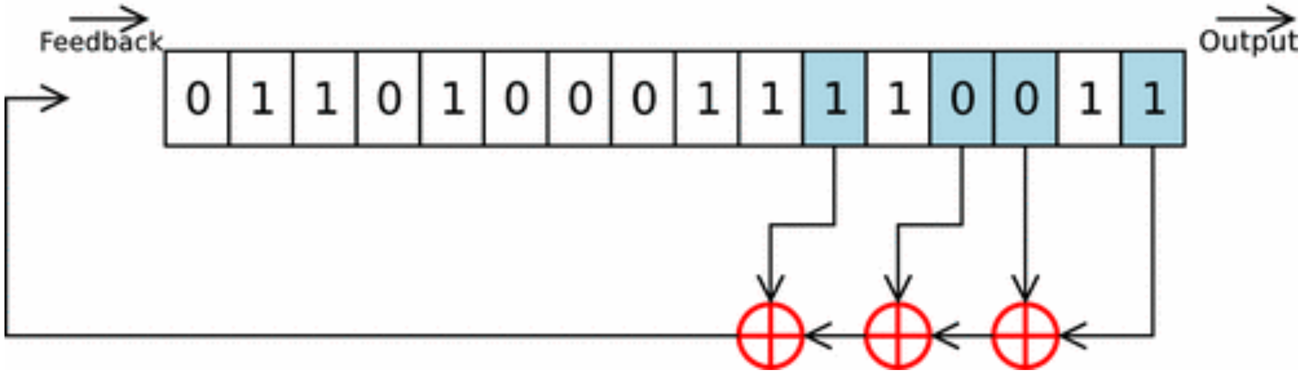


receiver

Categories of spreading (chipping) sequences

- Spreading Sequence Categories
  - Pseudo-random Noise (PN) sequences
  - Orthogonal codes
- For FHSS systems
  - PN sequences most common
- For DSSS beside multiple access
  - PN sequences most common
- For DSSS CDMA systems
  - PN sequences
  - Orthogonal codes

Generating a Pseudo-random Noise chip sequence with a linear feedback shift-register (LFSR)



number of registers: n

period: $N = 2^n - 1$

Properties of PN sequences:

- Property 1: In a PN sequence we have: $\Pr\{0\} = \dfrac{1}{2\cdot\left(1-\dfrac{1}{N}\right)}$ $\Pr\{1\} = \dfrac{1}{2\cdot\left(1+\dfrac{1}{N}\right)}$

$$\Pr\{0\} \approx \Pr\{1\} \approx \frac{1}{2} \quad \text{for } n \geq 10 \Rightarrow \frac{1}{N} \leq 10^{-3}$$

- Property 2: For a window of length n slid along output for N ($=2^n$-1) shifts, each n-tuple appears once, except for the all zeros sequence
- Property 3: The periodic autocorrelation of a PN sequence is:

$$R(\tau) = \begin{cases} 1 & \tau = 0, N, 2N, \ldots \\ -\dfrac{1}{N} & \text{otherwise} \end{cases}$$

Orthogonal Codes

- Orthogonal codes
  - All pairwise cross correlations are zero
  - Fixed- and variable-length codes used in CDMA systems
  - For CDMA application, each mobile user uses one sequence in the set as a spreading code
    - Provides zero cross correlation among all users
- Types
  - Walsh codes
  - Variable-Length Orthogonal codes

Walsh Codes

- Set of Walsh codes of length *n* consists of the n rows of an *n* x *n* Hadamard matrix:

$$H_1 = \begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix} \qquad H_k = \begin{pmatrix} H_{k-1} & H_{k-1} \\ H_{k-1} & \overline{H_{k-1}} \end{pmatrix}$$

- Sylvester's construction:

$$H_1 = \begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix} \qquad H_2 = \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 \end{pmatrix} \qquad \cdots$$

- Every row is orthogonal to every other row and to the logical not of every other row
- Requires tight synchronization
  - Cross correlation between different shifts of Walsh sequences is not zero

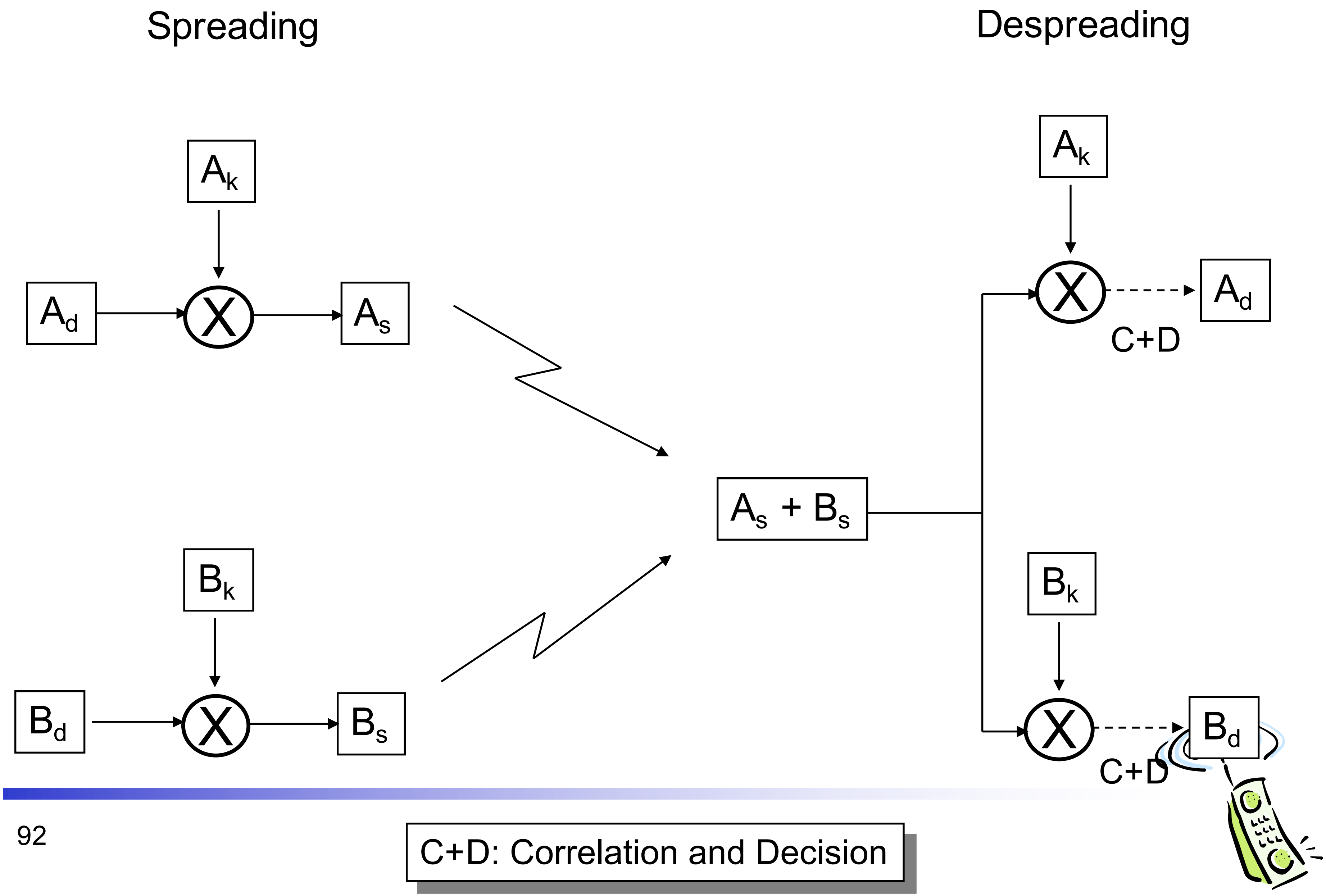
Typical Multiple Spreading Approach

- Spread data rate by an orthogonal code (channelization code)
  - Provides mutual orthogonality among all users in the same cell
- Further spread result by a PN sequence (scrambling code)
  - Provides mutual randomness (low cross correlation) between users in different cells

CDMA (Code Division Multiple Access)

- Principles
  - all terminals send on the same frequency and can use the whole bandwidth of the transmission channel
  - each sender has a unique code
  - The sender XORs the signal with this code
  - the receiver can “tune” into this signal if it knows the code of the sender
  - tuning is done via a correlation function
- Disadvantages:
  - higher complexity of the receiver (receiver cannot just listen into the medium and start receiving if there is a signal)
  - all signals should have approximately the same strength at the receiver
- Advantages:
  - all terminals can use the same frequency, no planning needed
  - huge code space (e.g., 2^{32}) compared to frequency space
  - more robust to eavesdropping and jamming (military applications…)
  - forward error correction and encryption can be easily integrated

CDMA: principle (very simplified)

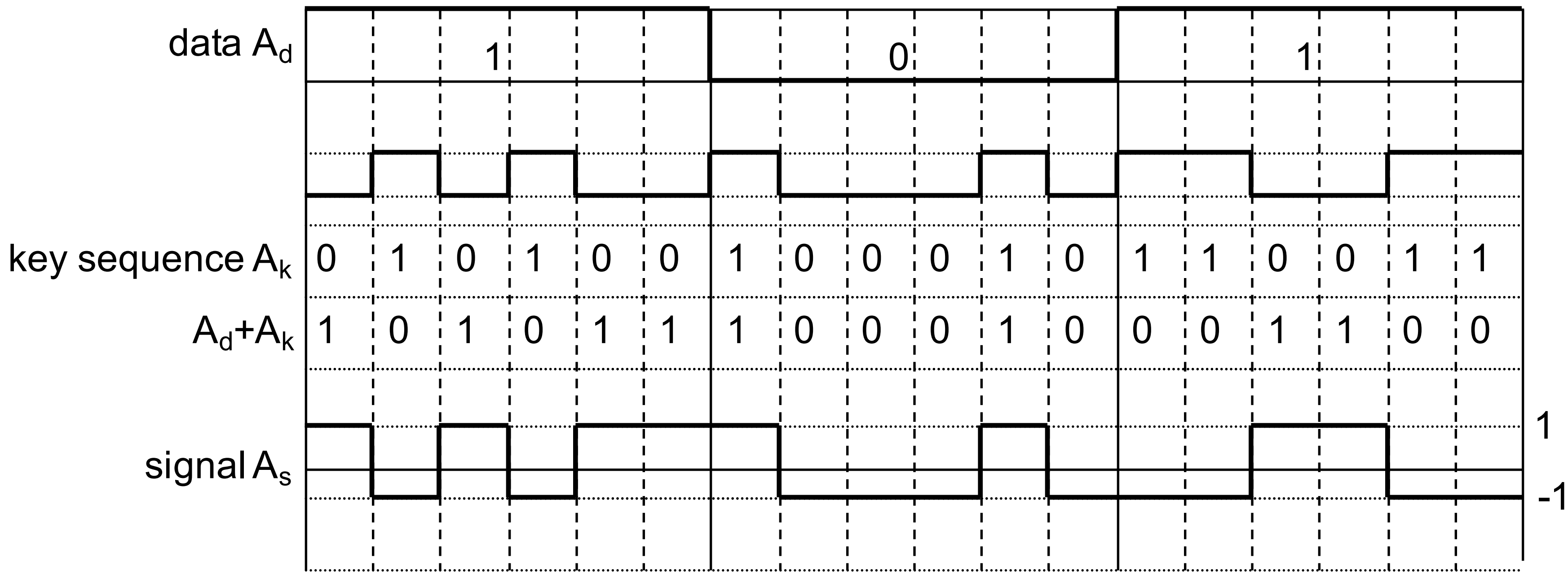


C+D: Correlation and Decision

CDMA: example

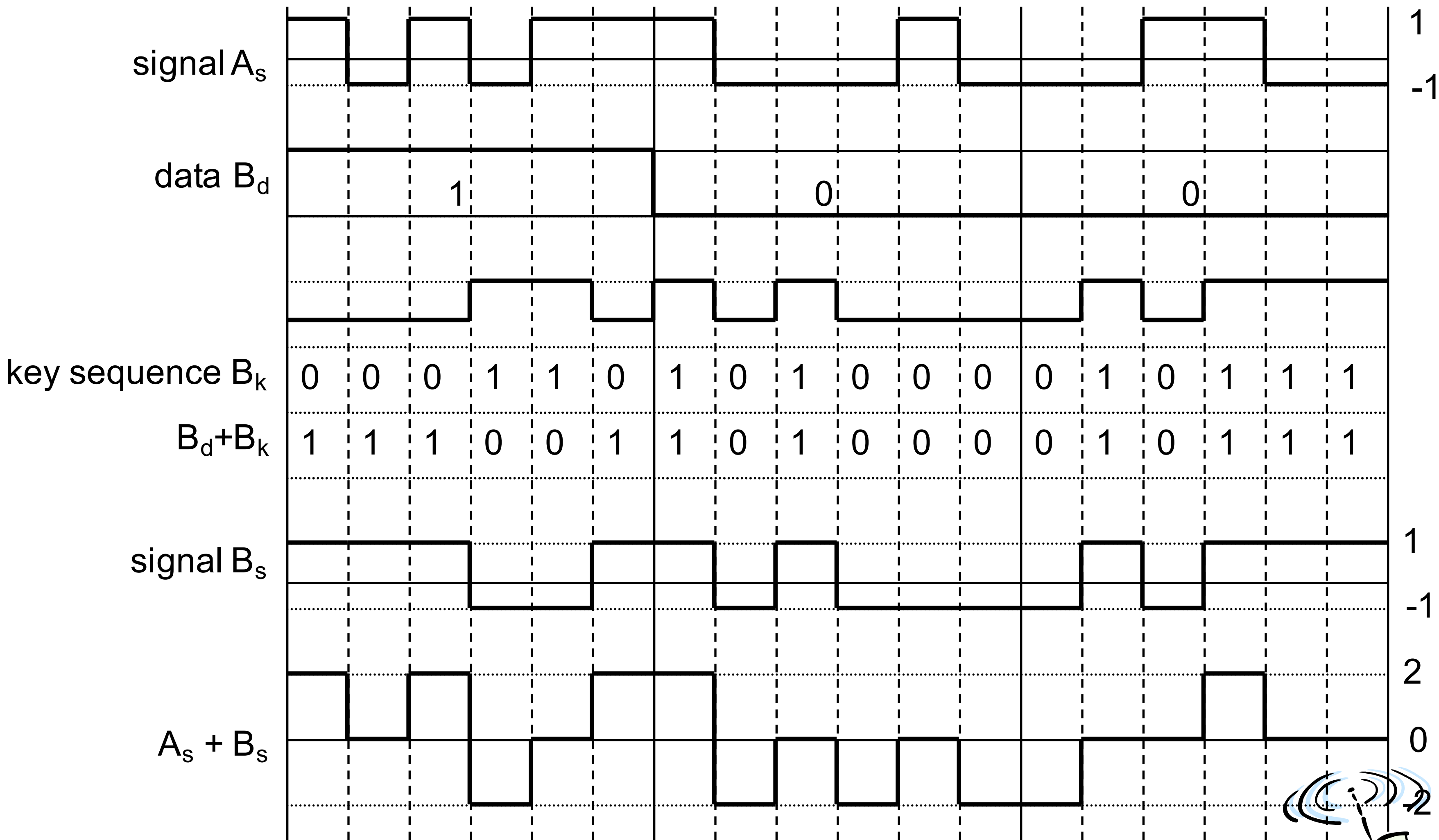
- Sender A
  - sends $A_d = 1$, key $A_k = 010011$ (assign: „0“= -1, „1“= +1)
  - sending signal $A_s = A_d * A_k = (-1, +1, -1, -1, +1, +1)$
- Sender B
  - sends $B_d = 0$, key $B_k = 110101$ (assign: „0“= -1, „1“= +1)
  - sending signal $B_s = B_d * B_k = (-1, -1, +1, -1, +1, -1)$
- Both signals superimpose in space
  - interference neglected (noise etc.)
  - $A_s + B_s = (-2, 0, 0, -2, +2, 0)$
- Receiver wants to receive signal from sender A
  - apply key A_k bitwise (inner product)
    - $A_e = (-2, 0, 0, -2, +2, 0)$ 🎬 $A_k = 2 + 0 + 0 + 2 + 2 + 0 = 6$
    - result greater than 0, therefore, original bit was „1“
  - receiving B
    - $B_e = (-2, 0, 0, -2, +2, 0)$ 🎬 $B_k = -2 + 0 + 0 - 2 - 2 + 0 = -6$, i.e. „0“

Spreading of signal A

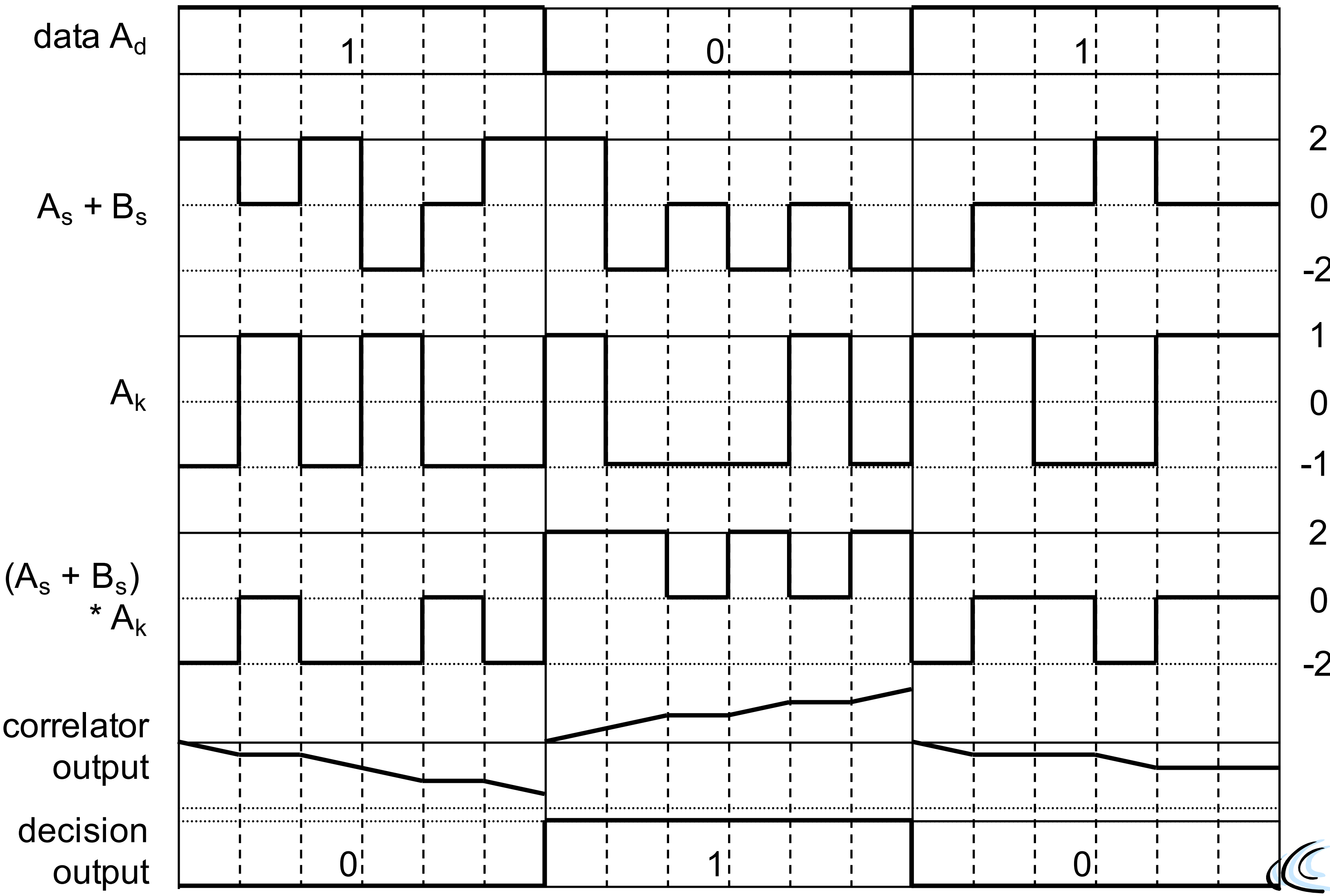


Real systems use much longer keys resulting in a larger distance between single code words in code space.

Spreading of signal B

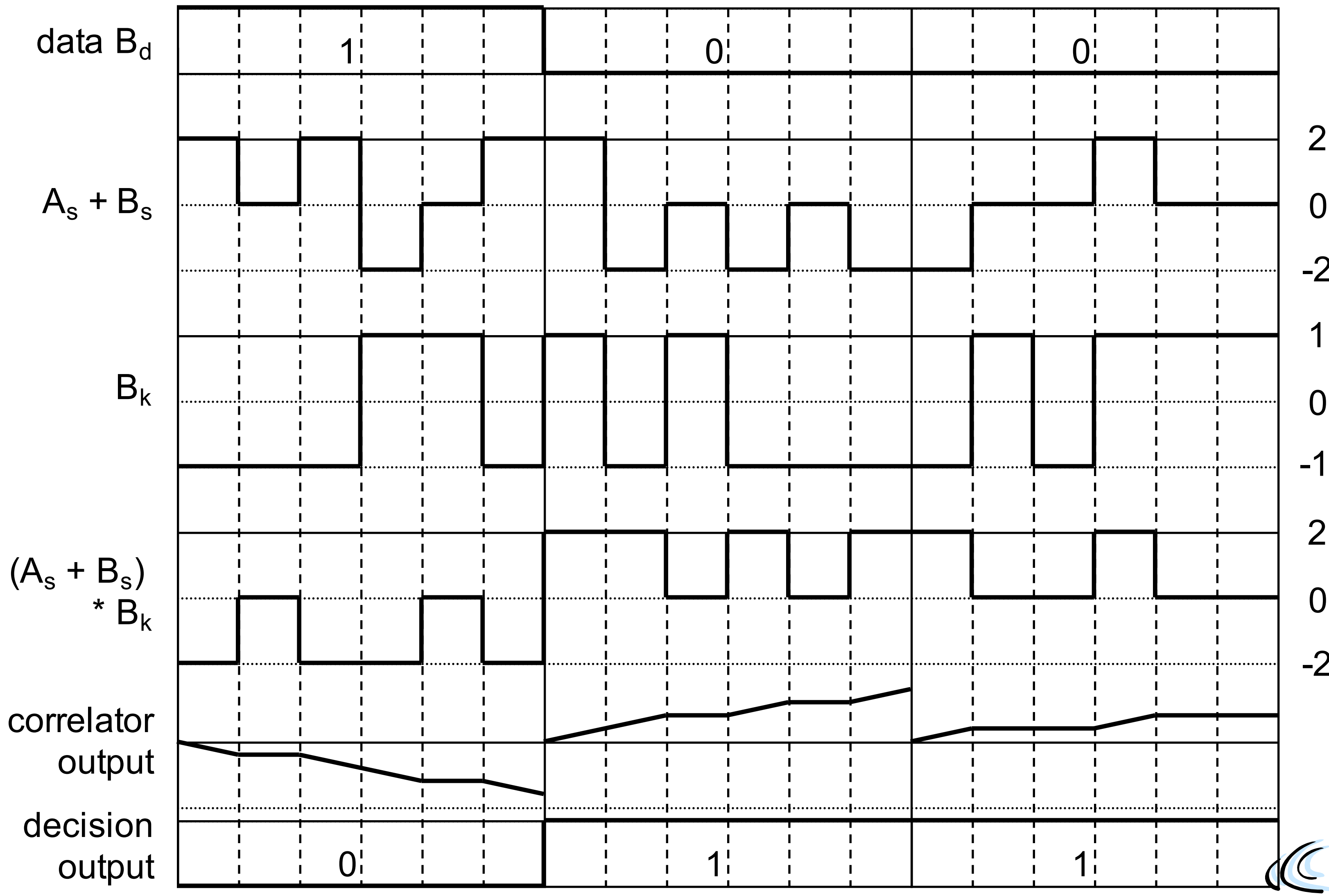


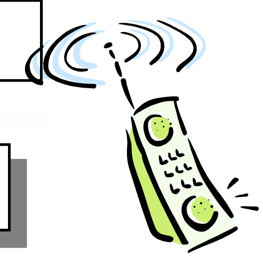
Despreading of signal A



Note: the received signal is inverted

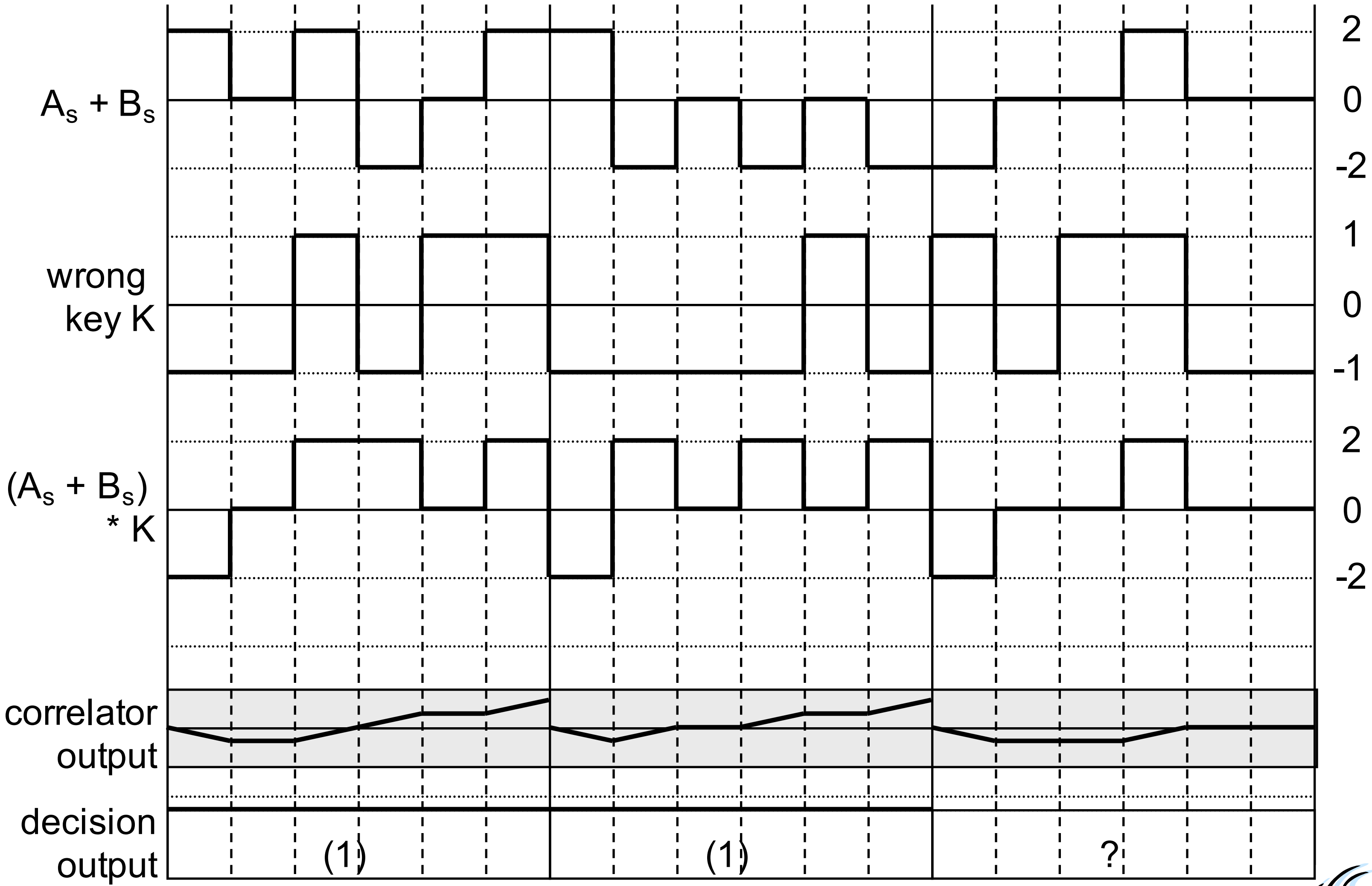
Despreading of signal B





Note: the received signal is inverted

Despreading with a wrong key



Comparison SDMA/TDMA/FDMA/CDMA

Approach	SDMA	TDMA	FDMA	CDMA
Idea	segment space into cells/sectors	segment sending time into disjoint time-slots, demand driven or fixed patterns	segment the frequency band into disjoint sub-bands	spread the spectrum using orthogonal codes
Terminals	only one terminal can be active in one cell/one sector	all terminals are active for short periods of time on the same frequency	every terminal has its own frequency, uninterrupted	all terminals can be active at the same place at the same moment, uninterrupted
Signal separation	cell structure, directed antennas	synchronization in the time domain	filtering in the frequency domain	code plus special receivers
Advantages	very simple, increases capacity per km²	established, fully digital, flexible	simple, established, robust	flexible, less frequency planning needed, soft handover
Dis-advantages	inflexible, antennas typically fixed	guard space needed (multipath propagation), synchronization difficult	inflexible, frequencies are a scarce resource	complex receivers, needs more complicated power control for senders
Comment	used in all cellular systems	standard in fixed networks, together with FDMA/SDMA used in many mobile networks	typically combined with TDMA (frequency hopping patterns) and SDMA (frequency reuse)	higher complexity

In practice, several access methods are used in combination

Example :SDMA/TDMA/FDMA for GSM